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Ozone Plumes from Small Cities and Ozone in High Pressure Weather Systems

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ABSTRACT

This report presents the results of a field investigation of ozone distribution and transports. The program focuses on the formation and transport of ozone in urban plumes of small cities and the behavior of ozone in a high pressure weather system traversing the eastern half of the United States. The field experiments were conducted in July - August 1977. Both ground level and airborne monitoring were conducted. The study was a collaborative effort involving Battelle-Columbus, the EPA Environmental Sciences Research Laboratory (ESRL), and Washington State University (WSU). This report concerns the aircraft and ground level measurements obtained by Battelle-Columbus, although some aircraft results by WSU and detailed hydrocarbon measurements by ESRL are presented. The report builds upon earlier investigations of ozone transport in the Ohio Valley and New England.

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SECTION 1

INTRODUCTION AND BACKGROUND

This report presents the results of a field investigation of ozone (O_3) distribution and transport conducted by Battelle, Columbus Laboratories under the sponsorship of the Environmental Protection Agency (EPA). The program focuses on the formation and transport of ozone in urban plumes of large and small cities, and the behavior of ozone in a high pressure weather system traversing the eastern half of the country. The program has involved detailed ground level and aircraft monitoring studies and the analysis and interpretation of the resulting data. This study builds upon earlier investigations of ozone transport in the Ohio Valley and New England.

The issue of ozone/precursor transport has caused a great deal of controversy, and this program was directed at providing additional information on various aspects of the controversy. Specifically, we have investigated the contribution of smaller cities to the downwind ozone burden and the long range transport of ozone associated with a high pressure system.

OBJECTIVES

The overall objective of the program is to determine the propensity of air masses to generate and transport ozone over long distances. Specific goals of the project are itemized below:

- to investigate the transport of ozone and precursors from urban areas, and especially to determine whether smaller cities contribute measurably to the downwind ozone burden
- to study the behavior of ozone associated with high pressure weather systems

- to improve current understanding of ozone variations with altitude, with emphasis on obtaining more data at higher altitudes (up to 20,000 feet MSL).

PROJECT DESCRIPTION

The field measurements obtained as part of this study are a significant contribution to the currently available data on atmospheric ozone distribution and transport. The measurements are crucial to the success of the program since they provide the data which will be used to address the program's objectives. The field experiments were conducted in July-August, 1977 in the midwestern U.S. Both ground level and airborne monitoring were conducted during the field experiments. Measurements were made from a single ground site and a twin engine research plane. The study was a collaborative effort involving Battelle-Columbus, EPA-ESRL, who provided a second ground monitoring station near St. Louis and detailed hydrocarbon analyses of our aircraft samples, and Washington State University (WSU), with whom we coordinated a number of aircraft operations. A comparison of the ozone monitors aboard the two aircraft (BCL and WSU) showed agreement within 2.5 percent.

The data from the field experiments are contained in appendices to this report. Much of the data is also summarized within the report itself.

SECTION 2

SUMMARY AND CONCLUSIONS

This report presents the results of a field investigation of atmospheric ozone distribution and transport conducted by Battelle's Columbus Laboratories under the sponsorship of the Environmental Protection Agency (EPA). The program focuses on the formation and transport of ozone in urban plumes of large and small cities, and the behavior of ozone in a high pressure weather system traversing the eastern half of the country.

The field experiments were conducted in July and August, 1977 in the midwestern U.S. Both ground level and airborne monitoring were employed.

This report describes the experimental aspects of the field program and an interpretation of the data as they relate to the program objectives. The study findings are summarized succinctly below.

- The St. Louis urban area generates an ozone plume with O_3 concentrations approaching 300 ppb under appropriate conditions.
- Smaller cities (populations $\leq$100,000) generate a measurable ozone plume under photochemically reactive conditions. The additional O_3 in the plumes is related to the cities' precursor emissions.
- During studies of ozone and precursors in a high pressure system traversing the eastern U.S., several layers rich in ozone were observed in vertical profiles. The upper layer of ozone, which was found between 10,000 and 15,000 feet MSL, was observed to cover nearly the entire eastern half of the U.S. (from Wisconsin to Virginia). Such a pervasive tropospheric O_3 layer has not been reported previously. The source of this ozone layer was demonstrated to be the stratosphere.
- Analysis of our vertical profile results and rawindsonde data during the high pressure system study suggests that the pervasive O_3 layer observed over the eastern U.S. at 10,000-15,000 feet MSL resulted from an injection of stratospheric air into the troposphere during cyclogenesis

in northern Canada several days before our observations over the U.S. If this is the case, then the persistence of O_3 in this elevated layer must be at least 3-4 days.

- During the high pressure system study, ozone concentrations near the surface increased steadily over the three days that it took the high to cross the eastern U.S. During flights over rural areas, concentrations of 30-40 ppb were observed on the first day over Wisconsin, 70-90 ppb on the second day over Ohio, and >100 ppb on the third day over Pennsylvania.

SECTION 3

SAMPLING SITES

Chemical and meteorological monitoring during the field program made use of two mobile laboratories situated at Civic Memorial Airport in Bethalto, Illinois. The location of Civic Airport is noted in Figure 1. The site is approximately 36 km northeast of downtown St. Louis. Civic Airport is far enough removed from St. Louis proper that the density of air traffic is tolerable for an airborne study such as this. Nevertheless, air traffic occasionally caused deviations in our flight patterns and frequently dictated the location of the 20,000' vertical atmospheric profiles which were planned as an integral part of the study.

The mobile laboratories were positioned next to the hanger used for the research plane. This greatly facilitated communications and provided for rapid sample bag transfer and analysis in the mobile labs. However, local airport emissions from taxiing planes and other sources precluded collection of meaningful ground level hydrocarbon data at this site. Detailed ground level hydrocarbon data representative of the area were obtained by EPA-ESRL scientists at a location approximately 13 km southeast of Civic Airport.

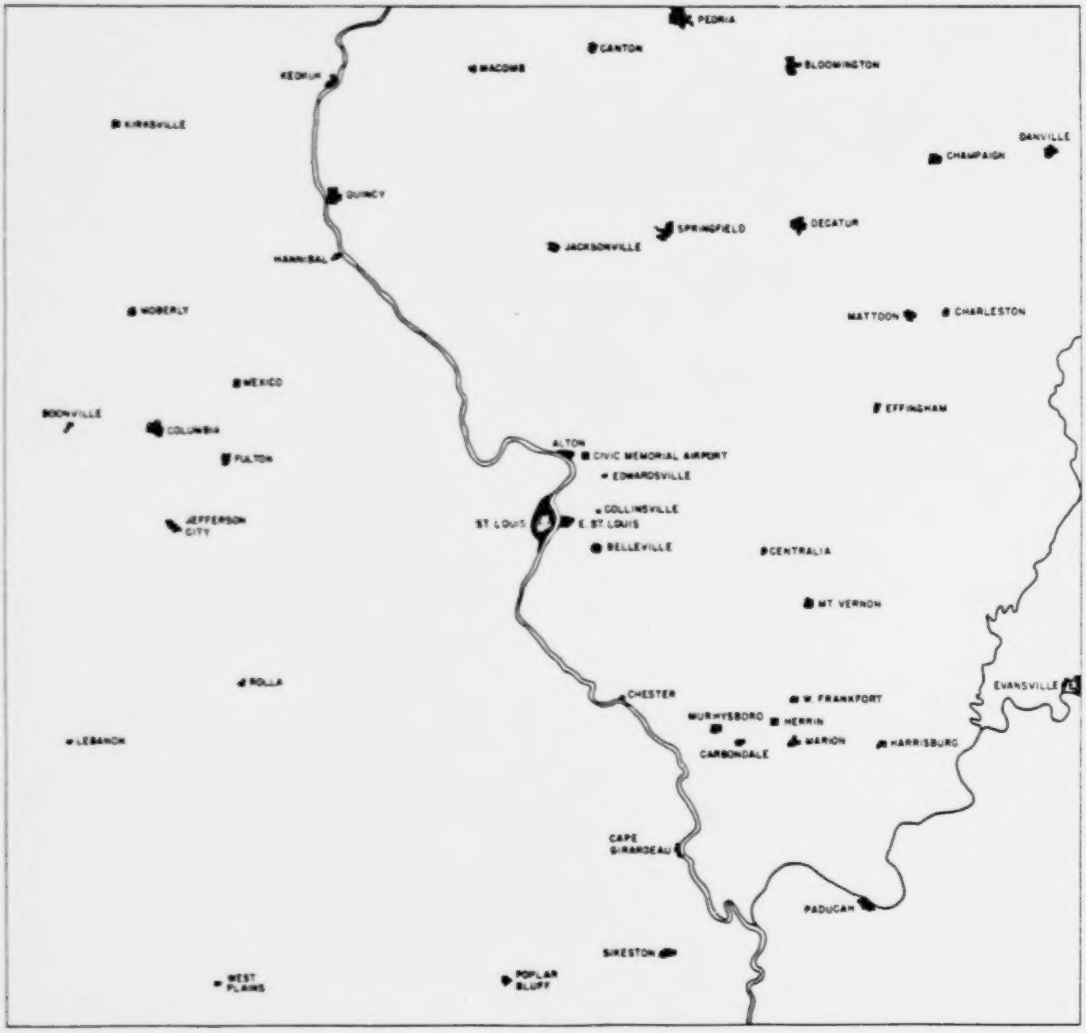


Figure 1. St. Louis area showing Civic Memorial Airport where mobile labs were located.

SECTION 4

EXPERIMENTAL METHODS

The field experiments made use of the Battelle mobile lab, shown in Figure 2, as well as a smaller mobile laboratory and an instrumented aircraft. The two mobile laboratories were located side by side at Civic Memorial Airport in Bethalto, Illinois. The mobile labs served both as continuous ground monitoring stations and as support laboratories for the airborne operations. Ground-level monitoring data were collected continuously, 24 hours a day at the mobile labs.

The variables measured at the mobile laboratories are listed in Table 1. The measurement techniques and instruments are also tabulated. Details of the operation and calibration of the instruments have been presented elsewhere(1,2). The ground-level NMHC and CH_4 measurements at the airport were so influenced by local airport emissions that these data have been deleted from the report.

Aircraft Measurements

The airborne sampling platform utilized during this study was the Battelle Cessna 411 research aircraft pictured in Figure 3. This twin-engine all-weather aircraft was equipped at the start of the study for measurements listed in Table 2. Most flights were conducted at 1000 feet AGL (above ground level). Power was supplied to the instruments listed in Table 2, as well as recorders and data acquisition system, from a 1.0 KVA power inverter supplied from two 100-amp 28-volt alternators. The instruments were operated 24 hours a day on ground power and instantaneously switched to aircraft power just prior to takeoff.

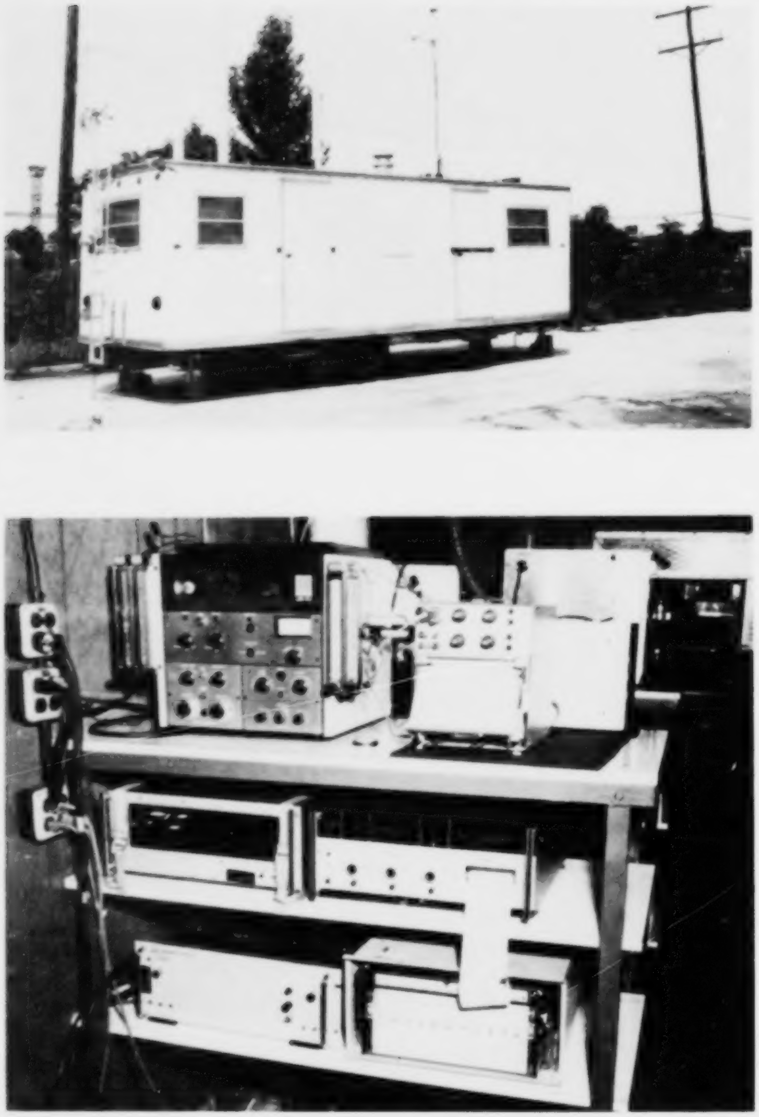


FIGURE 2. BATTELLE MOBILE AIR QUALITY LABORATORY

TABLE 1. ST LOUIS GROUND STATION MEASUREMENTS

Measured Variable	Technique	Instrument
O_3	Chemiluminescence	Bendix 8002
NO	Chemiluminescence	Bendix 8101-B
NO_x	Chemiluminescence	Bendix 8101-B
PAN	Electron Capture G.C.	Varian 1200
$HONO_2$	Coulometry	Battelle Modified Mast
Fluorocarbon-11	Electron Capture G.C.	Varian 1200
NMHC	FID Gas Chromatography	Beckman Model 6800
CH_4		
CO		
Mass Loading	HiVol/weighing	Cahn Microbalance
NO_3^-	HiVol/Ion Chromatography	D-ion-x Model 10
$SO_4^=$	HiVol/Ion Chromatography	D-ion-x Model 10
NH_4	HiVol/Gas Sensing Electrode	Orion NH_3
C,H,N	HiVol/Combustion-Thermal Conductivity	Perkin-Elmer 240
Temperature	Automated Weather Station	MRI Model 802
Relative Humidity	Automated Weather Station	MRI Model 907
Wind Speed	Automated Weather Station	MRI Model 1074-2
Wind Direction	Automated Weather Station	MRI Model 1074-2
Global Radiation Intensity	180° pyrheliometer	Eppley

TABLE 2. AIRCRAFT MEASUREMENTS

Specie	Instrument	Technique
O_3	REM Model 602	Gas phase chemiluminescence
NO_x	TECO Model 14D	Chemiluminescence
$HONO_2$	TECO Model 14D	Chemiluminescence
NO_3^-	High Volume Sampler	High Volume collection on quartz filters/ion chromatography
Fluorocarbon-11(a)	Varian Hi Fi III	Electron capture G.C.
Detailed C_2-C_{10} Hydrocarbons(a,b)	Perkin-Elmer 900	Cryogenic concentration and FID G.C.(b)
Temperature	Metrodata M8	Shielded thermistor
Dew Point	Cambridge System 137-C3	Condensation

(a) Samples collected in Tedlar bags

(b) Analyses performed by W. Lonneman, R. Kuntz, and S. Meeks of EPA.

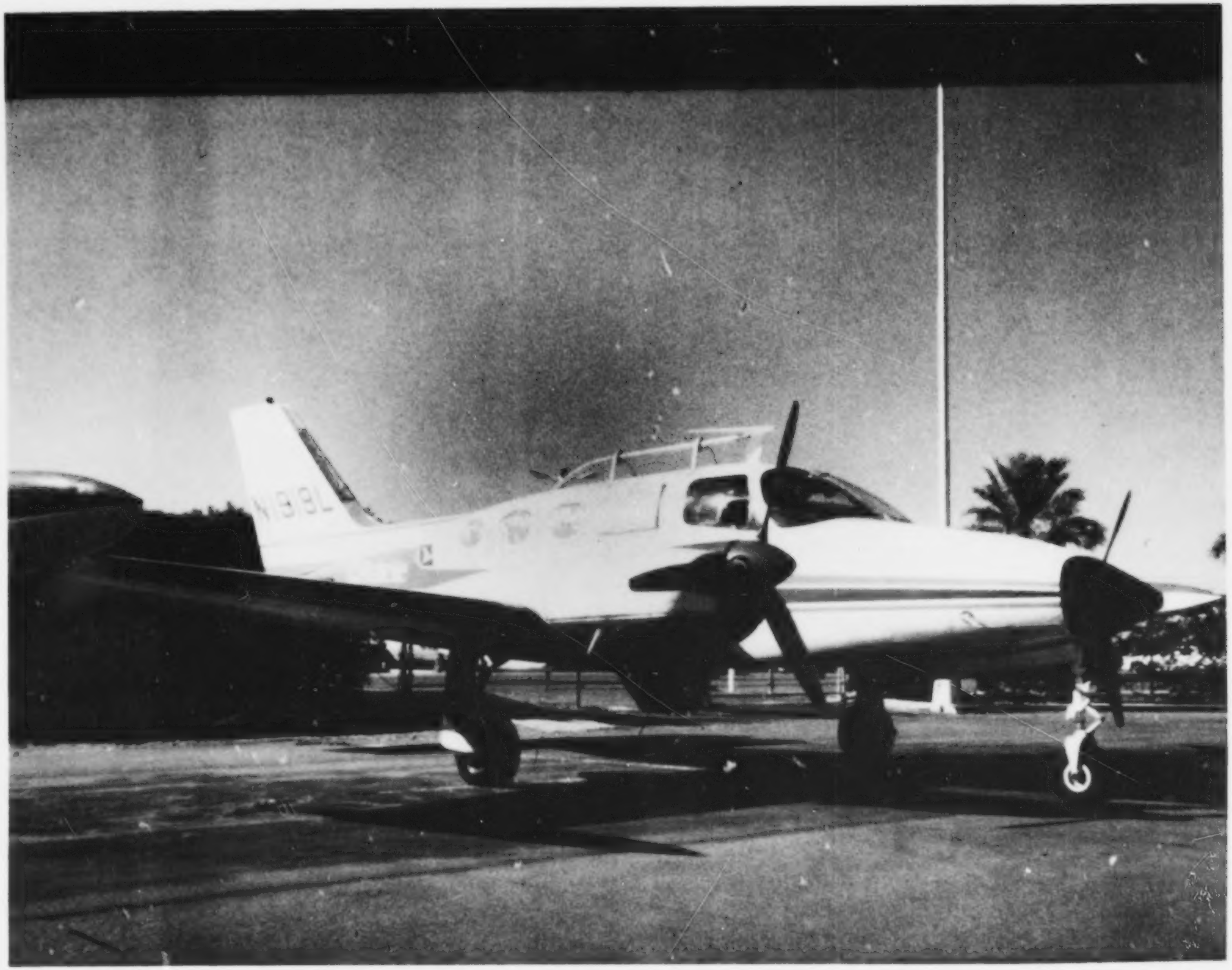


FIGURE 3. AIRCRAFT SAMPLING PLATFORM

The gas monitoring instruments obtained their samples from excess ram air which entered the plane through a stainless-steel sampling probe. Each instrument was connected to the sample manifold by Teflon tubing. Tedlar sampling bags were filled through Teflon tubing containing a variable stainless steel orifice. Ram pressure was used to fill the bags. Each bag was evacuated, tested for leaks, backfilled with zero nitrogen and evacuated twice more in the mobile lab prior to loading aboard the aircraft. Each bag was evacuated again on board the plane just prior to sample collection. The final evacuation aboard the aircraft used the TECO 14-D vacuum pump. This procedure ensures negligible contamination or carry-over in the sample bags, at least for the compounds of interest in this study.

Quartz filters (61 mm diameter) were used for aerosol sampling aboard the aircraft. The high volume sampler on the plane used a separate stainless steel probe extending out the roof of the cockpit with a gentle bend. This probe can be seen in Figure 3. The aircraft samples were collected at a flow rate of 0.3 m^3/min. Several filters were preloaded in individual filter holders specially designed for this application. The preloaded filters could be changed easily during a flight, permitting separate aerosol collections over different portions of the flight path. After each flight, the filters were stored in individual glassine envelopes and sealed in separate plastic bags.

The aircraft filters were analyzed and the gas monitoring instruments were calibrated in the same manner as described earlier. The chemiluminescent nitric acid monitor used on the plane has been described elsewhere(3).

Signals from the O_3, NO_x, $HONO_2$, and temperature monitors were continuously recorded by two dual-pen strip chart recorders. These signals, as well as time and dew point, were also recorded on a Pertec magnetic tape data acquisition system.

SECTION 5

RESULTS

GROUND MONITORING RESULTS

Daily air quality and meteorology are summarized in Table 3 for each day of the St. Louis area study. Both 24-hour averages and 1-hour maxima are tabulated for several key pollutants. Total suspended particulate (TSP) results are also presented. These data were collected from two mobile laboratories located in Bethalto, Illinois at Civic Memorial Airport approximately 36 km northeast of downtown St. Louis.

A daily tabulation of the detailed air quality and meteorology data is included in Appendix A of this report. The symbol -1.00 in these and other tables indicates no data for the specified time period. Hourly averages are reported in central daylight time (CDT). Data were collected 24 hours a day and are tabulated starting with the 1000 CDT average each day to correspond with the start of the daily high volume aerosol collection. Thus the daily averages have been computed over the same times as the high volume collections.

Some short-term high concentrations of primary pollutants appear periodically throughout the daily data tables. These values frequently were caused by planes warming up or taxiing near the mobile laboratories. As mentioned earlier, the continuous hydrocarbon data were so influenced by this and other local airport emission sources that the data have been deleted from the tables, so as not to mislead the reader. Since the study was designed almost exclusively around the aircraft results, the objectives are in no way compromised by the missing ground level hydrocarbon data.

Twenty-four hour high volume sampling was conducted at the mobile laboratory site at Civic Airport using quartz fiber filters as the collection medium. The TSP data and results of inorganic analyses of the filters are shown in Table 4. The filters were analyzed for ammonium, nitrate and

TABLE 3. SUMMARY OF AIR QUALITY DATA - BETHALTO, ILLINOIS

Date	General	Temp. °C[a]	R.H.%[b]	Aerosol Mass Loading, μg/m^3	24-Hour Average O_3, ppm	24-Hour Average NO_x, ppm	24-Hour Average PAN, ppm	24-Hour Average F-11, ppt	24-Hour Average CO, ppm	1-Hour Maximum O_3, ppm	1-Hour Maximum NO_x, ppm	1-Hour Maximum PAN, ppm
7-7-77	Hot, Humid	37.1	76	-	.049	.009	-	270	-	.102	.026	-
7-8-77	Warm, Hazy	33.1	88	48.6	.041	.010	-	212	-	.076	.063	-
7-9-77	Warm, Sunny	31.9	78	31.4	.057	≤.005	-	201	-	.088	.016	-
7-11-77	Rain	-	92	49.1	.036	.014	-	440	.43	.072	.034	-
7-12-77	Overcast, Humid	-	76	49.8	.035	.026	.002	377	1.03	.072	.045	.006
7-13-77	Hot, Humid	39.1	78	70.8	.047	.016	≤.001	548	2.72	.155	.033	.005
7-14-77	Hot, Humid	40.6	74	72.5	.062	.012	.008	235	.94	.159	.036	.009
7-15-77	Hot, Humid	39.1	75	104.3	.061	.020	-	202	.35	.150	.055	-
7-16-77	Hot, Humid	37.5	72	118.9	.073	.009	≤.001	229	.55	.142	.027	.005
7-18-77	Hot, Hazy	37.8	72	86.5	.054	≤.005	.004	220	.66	.118	.034	.008
7-19-77	Hot, Humid	39.4	75	-	.063	≤.005	.004	268	.51	.146	.020	.014
7-20-77	Hot, Sunny	36.0	78	47.5	.034	.006	≤.001	296	.37	.059	.034	.002
7-21-77	Warm, Rain	35.7	90	-	.047	≤.005	.002	196	.52	.116	.038	.008
7-22-77	Overcast, Warm	30.5	78	38.9	.038	≤.005	≤.001	157	.79	.077	.011	.002
7-25-77	Cloudy	30.3	86	25.2	.047	.007	≤.001	153	.32	.080	.013	.002
7-26-77	Clear, Sunny	-	-	20.6	.028	≤.005	≤.001	159	.32	.050	.012	.002
7-27-77	Clear, Sunny	-	-	46.1	.044	.014	.001	353	.50	.086	.039	.003
7-28-78	Sunny, Hazy	-	-	87.7	.068	.023	.003	287	.63	.153	.063	.008
7-29-77	Overcast ⟶ Sunny	-	-	60.0	.034	.034	.002	300	.57	.146	.100	.023
7-30-77	Warm, Clear	-	-	46.6	.060	.012	.003	208	.40	.149	.036	.018
8-1-77	Sunny, Clear	-	54	43.6	.024	.013	≤.001	224	.34	.044	.054	.002
8-2-77	Overcast	26.9	58	-	.039	.032	.002	254	.56	.080	.055	.005
8-3-77	Sunny	20.6	58	62.1	.056	.018	.002	230	.41	.113	.081	.005

(a) 1-hour max.

(b) 24-hour avg.

TABLE 4. AEROSOL RESULTS FROM BETHALTO, ILLINOIS ($\mu g/m^3$*)

Date	Total Mass	NH_4^+	NO_3^-	$SO_4^=$
7/8/77	48.6	0.64	0.50	5.30
7/9/77	31.4	1.15	0.30	5.94
7/11/77	49.1	1.12	2.86	9.45
7/12/77	49.8	0.82	0.29	6.58
7/13/77	70.8	1.17	0.27	10.29
7/14/77	72.5	2.10	0.14	13.11
7/15/77	104.3	7.45	0.13	32.61
7/16/77	118.9	11.73	0.07	40.19
7/17/77**	85.1	9.07	0.05	39.68
7/18/77	86.5	5.95	0.06	19.57
7/20/77	47.5	1.70	0.07	11.30
7/22/77	38.9	2.55	0.06	10.00
7/25/77	25.2	2.47	0.05	6.98
7/26/77	20.6	0.96	0.15	2.05
7/27/77	46.1	--	0.14	13.12
7/28/77**	87.7	7.64	0.12	29.72
7/29/77	60.0	3.23	0.26	10.34
7/30/77**	46.6	3.60	0.07	8.90
8/1/77	43.6	2.53	0.27	5.00
8/3/77	62.1	3.02	0.45	10.24
Avg.	63.6	3.91	0.36	14.41

* Minimum Detectable Limits

Total - 0.1 $\mu g/m^3$

NH_4^+ - 0.01 $\mu g/m^3$

NO_3^- - 0.03 $\mu g/m^3$

$SO_4^=$ - 0.01 $\mu g/m^3$

** Partial sampling day

sulfate. Episodes of high sulfate concentration are evident from the data. Ammonium generally followed the same trend as the sulfate concentration. The amount of nitrate present at Civic Airport was less than 0.5 $\mu g/m^3$ on all days but two.

Aircraft Results

Twenty-seven aircraft sampling flights were conducted during the study. Flight patterns for each of the sampling missions are mapped in Appendix B. Ozone and NO_x were monitored continuously during the flights. Two maps for each flight are included in Appendix B, one showing O_3 concentrations and one representing NO_x. Sampling was at 1000 feet AGL unless noted otherwise. Locations of spirals and bag sample collection points are marked on the maps.

Vertical profiles of O_3, temperature and dew point are also included in Appendix B and are keyed to the flight maps. The vertical O_3 profiles have been corrected for atmospheric density. Results of fluorocarbon 11 determinations from the bag samples from each flight are shown in Table 5. Detailed C_2-C_{10} hydrocarbon analyses were performed on each aircraft bag by EPA scientists at the EPA mobile laboratory located approximately 13 km southwest of our site. The results of these analyses are available elsewhere.$^{(4)}$ Pertinent portions of the hydrocarbon data will be presented and discussed later in this report.

Results of ion chromatographic analysis of the high volume filters collected aboard the aircraft are listed in Table 6. The concentrations reported for filters collected over short times should be used with caution since the amounts of NO_3^- and $SO_4^=$ collected on the filters were only slightly greater than the filter blanks.

TABLE 5. FLUOROCARBON 11 RESULTS FROM AIRCRAFT BAGS (ppt)

Date	Flight No.	Bag 1	Bag 2	Bag 3	Bag 4	Bag 5	Bag 6	Bag 7	Bag 8
7/09/77	1	-1							
7/12/77	2	-1							
7/15/77	4	142	121	94	132	86	128	170	188
7/20/77	5	-1	277	99	120	123	131		
7/21/77	6	151	140	226	144	313			
7/21/77	7	135	120	168					
7/22/77	8	-1	228	150					
7/23/77	9	-1	194	226	243	218	227	192	-1
7/24/77	10	186	-1	-1	179				
7/27/77	12	207	217	142	188	186	326	199	
7/28/77	13	115	141	115	123	139	165		
7/28/77	14	216	214	223	146	154	160		
7/29/77	15	153							
7/29/77	16	139	173						
7/30/77	17	191	174						
7/30/77	18	133							
7/30/77	19	143	152	125					
8/01/77	20	122	153	135	126				
8/01/77	21	142	133	142	133	132	124		
8/03/77	22	148	142	145					
8/03/77	23	193	180	157	137				
8/04/77	24	292	153	190	201	143			
8/04/77	25	132	150	262					
8/04/77	26	158	115	139					

(a) A-1 entry indicates missing data.

TABLE 6. AIRCRAFT HIGH VOLUME FILTER RESULTS

Flight	Date	Filter No.	Volume, (m^3)	NO_3^-, $\mu g/m^3$	$SO_4^=$, $\mu g/m^3$
10	7-24-77	2	21.6	<0.2	29.1
12	7-27-77	1	6.9	3.2	8.1
14	7-28-77	1	3.3	2.1	29.7
		2	5.2	1.3	18.1
		3	5.2	0.9	16.1
		4	5.7	<0.9	15.4
15	7-29-77	1	51.9	0.4	2.4
16	7-29-77	1	50.3	1.1	1.7
		2	25	0.8	2.1
18	7-30-77	1	16.5	0.6	4.4
19	7-30-77	1	25.6	<0.2	8.7
22	8-03-77	1	8.1	6.3	17.0
		2	7.2	2.1	5.0
		3	8.6	2.1	5.9
23	8-03-77	1	6.8	1.5	3.4
		2	7.4	1.6	2.6
27	8-04-77	1	11.4	1.4	9.3
		2	14.4	<0.3	6.9
		3	5.7	1.0	12.1

SECTION 6

ANALYSIS AND INTERPRETATION

The two major goals of this study are:

(1) to determine the contribution of cities of moderate population ($\leq$100,000) to downwind ozone concentrations and

(2) to define the horizontal and vertical extent of high ozone concentrations within a high pressure system traversing the U.S.

Experiments designed to resolve these two questions account for the majority of the aircraft monitoring flights. Ozone plumes from cities of different size will be discussed first, followed by analysis of a study of O_3 in a high pressure system.

URBAN OZONE PLUMES

Ozone plumes from a number of major U.S. cities have been studied during the last few years. In view of all the evidence, few atmospheric scientists would dispute that high concentrations of O_3 are generated and transported downwind in the plumes of large cities such as Los Angeles, New York, and St. Louis. However, there are numerous moderate-size cities which are affected by controls on emission of ozone precursors. The contribution of these cities to the downwind O_3 burden has not been well documented. Consequently, a major portion of this study was devoted to airborne investigations of ozone plumes from various size cities. The important question to be answered is whether smaller cities contribute measurably to the downwind O_3 level. To answer this question, upwind and downwind traverses were performed in the vicinity of a large and a moderate-size city on several different days. The traverses were flown perpendicular to the wind direction. The data have been examined for ΔO_3 (O_3 downwind - O_3 upwind) as an indication of the city's ozone plume. Several of these experiments will be described shortly. First, however, a review of the characteristics of urban ozone plumes is in order.

Ozone Plumes from Major Metropolitan Areas

Clearly defined ozone plumes are frequently observed downwind of major centers of population and industry on photochemically active days. Such a plume has been observed downwind of St. Louis(5) and was mapped by a few flights during the present study for comparison with the plumes of smaller urban areas. On July 9, 1977, upwind and downwind patterns were flown around St. Louis to search for the city's plume. The results from this flight are presented in Figure 4. The ΔO_3 is unmistakable, with upwind concentrations averaging 70 ppb and downwind levels reaching 130 ppb. Another example of the St. Louis O_3 plume observed during this program is shown in Figure 5. Data from the afternoon flight of July 28, 1977 have been used to draw contours representing O_3 concentrations downwind of St. Louis at 1000' AGL. Various shadings represent the O_3 levels within the contour areas. The plume character of the downwind concentrations is obvious.

Urban O_3 plumes from a number of major cities have been observed and characterized in recent years. Examples of ozone plumes from other major cities will give perspective to this discussion. Two examples of downwind traverses of the Phoenix, Arizona, plume(6) are shown in Figures 6 and 7. These traverses were carried out over the desert, where sources of interfering emissions are minimal. In both cases the plume O_3 can be clearly distinguished from ambient background ozone concentrations.

The New York metropolitan area generates an ozone plume which was mapped on several days in the summer of 1975. Figure 8 shows the New York plume at two different times on July 24, 1975(7). Winds on 24 July were from the southwest, and trajectories show that the location of the high ozone concentrations over central Connecticut coincided with the position of the morning precursor emissions from New York after the corresponding transport time. The shape of the plume in the horizontal plane is clear from Figure 8. A vertical outline was obtained on 10 August, 1975, by making both vertical and horizontal O_3 measurements downwind of New York perpendicular to the wind direction. This cross-sectional pattern resulted in the O_3 distribution depicted in Figure 9. The darkly shaded

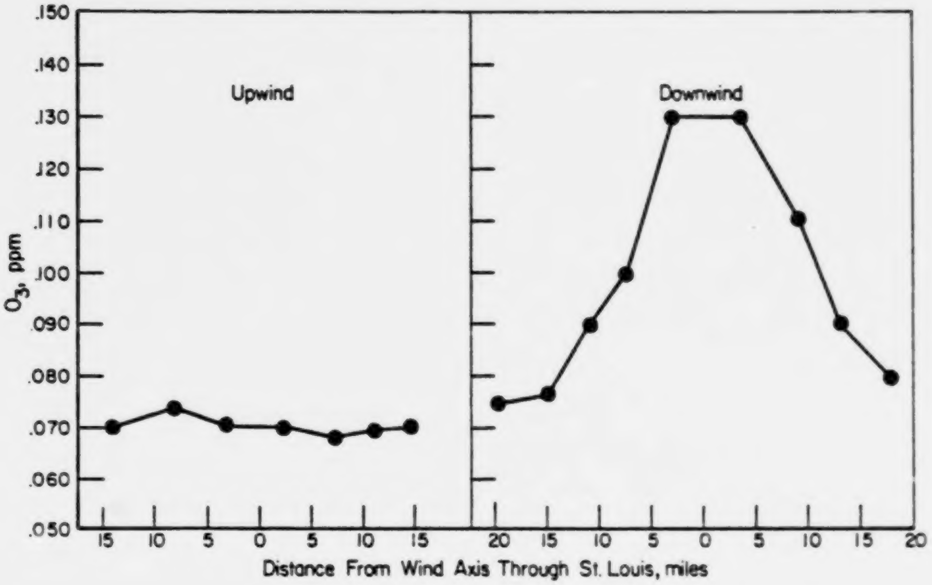


Figure 4. Ozone concentrations along upwind and downwind traverses of St. Louis on July 9, 1977.

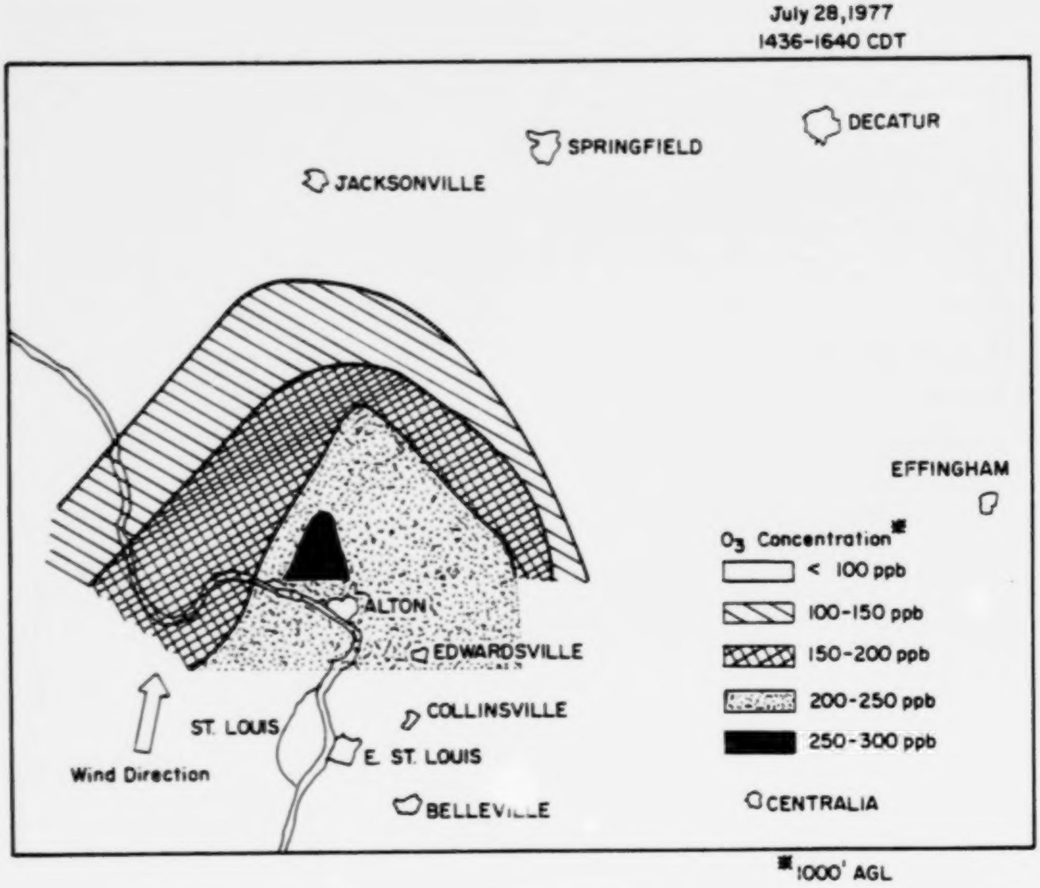


Figure 5. Distribution of O_3 downwind of St. Louis, July 28, 1977.

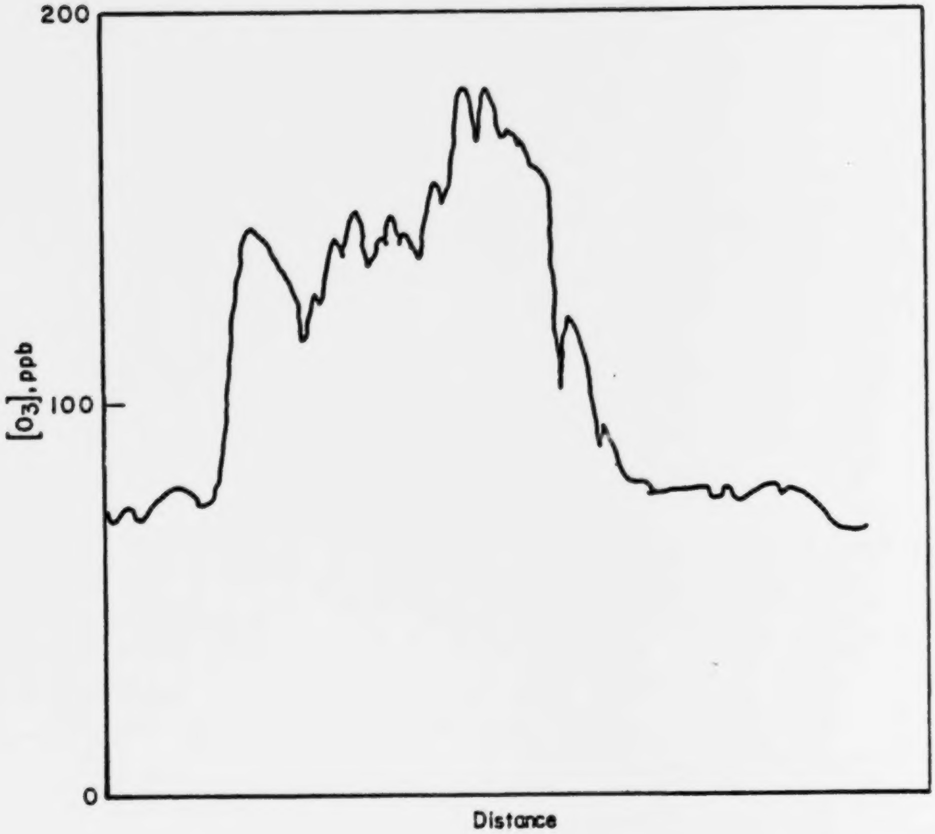


Figure 6. Cross section of Phoenix, AZ plume, October 14, 1977.

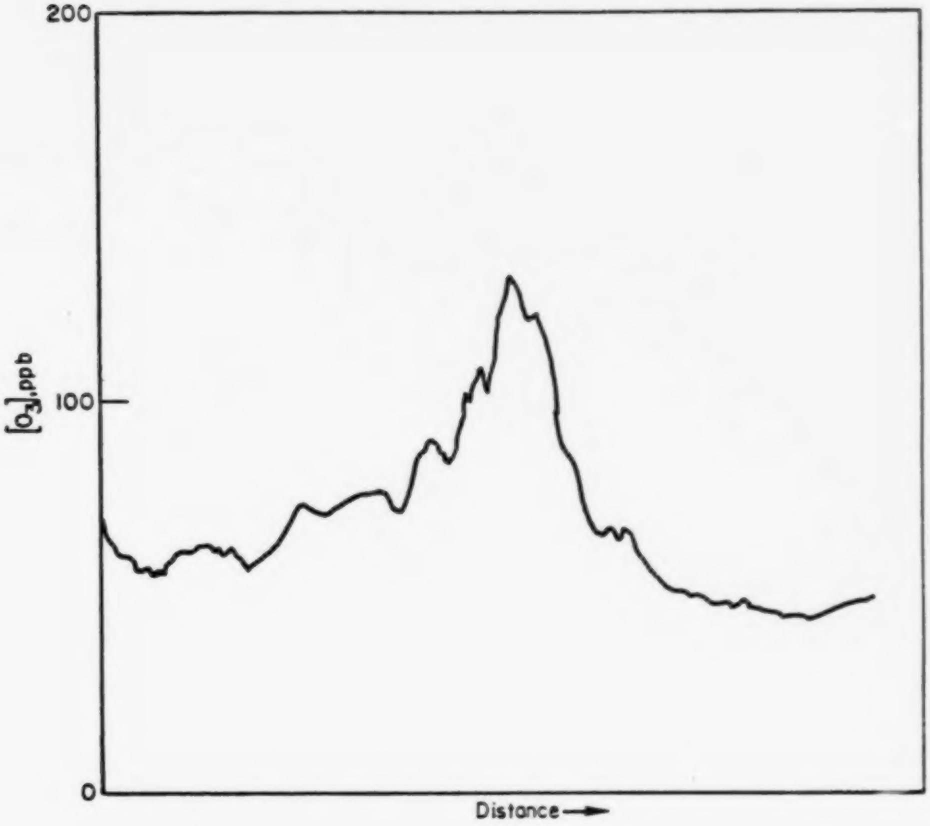


Figure 7. Cross section of Phoenix, AZ plume, October 18, 1977.

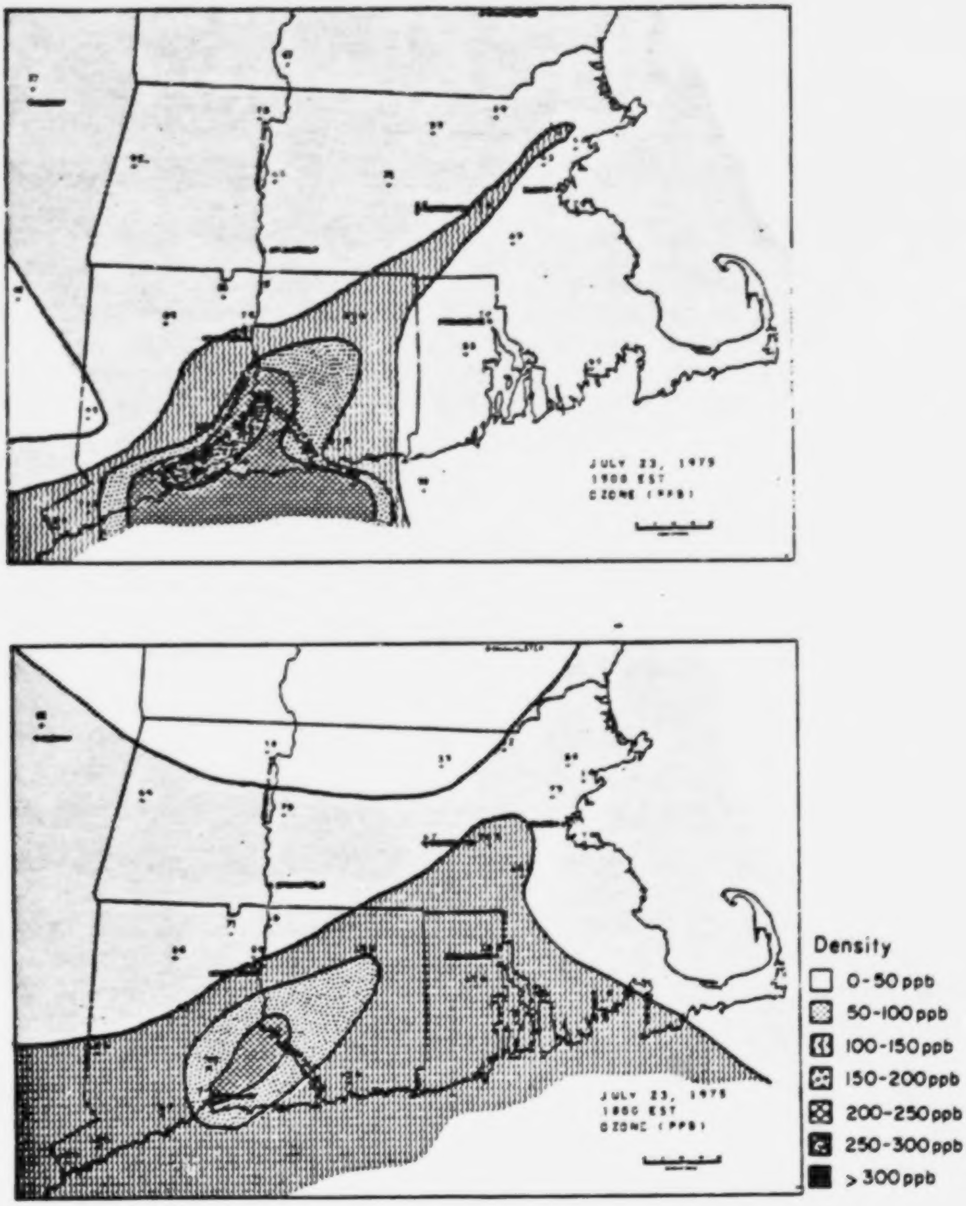


Figure 8. Ozone distribution in southern New England on July 23, 1975.

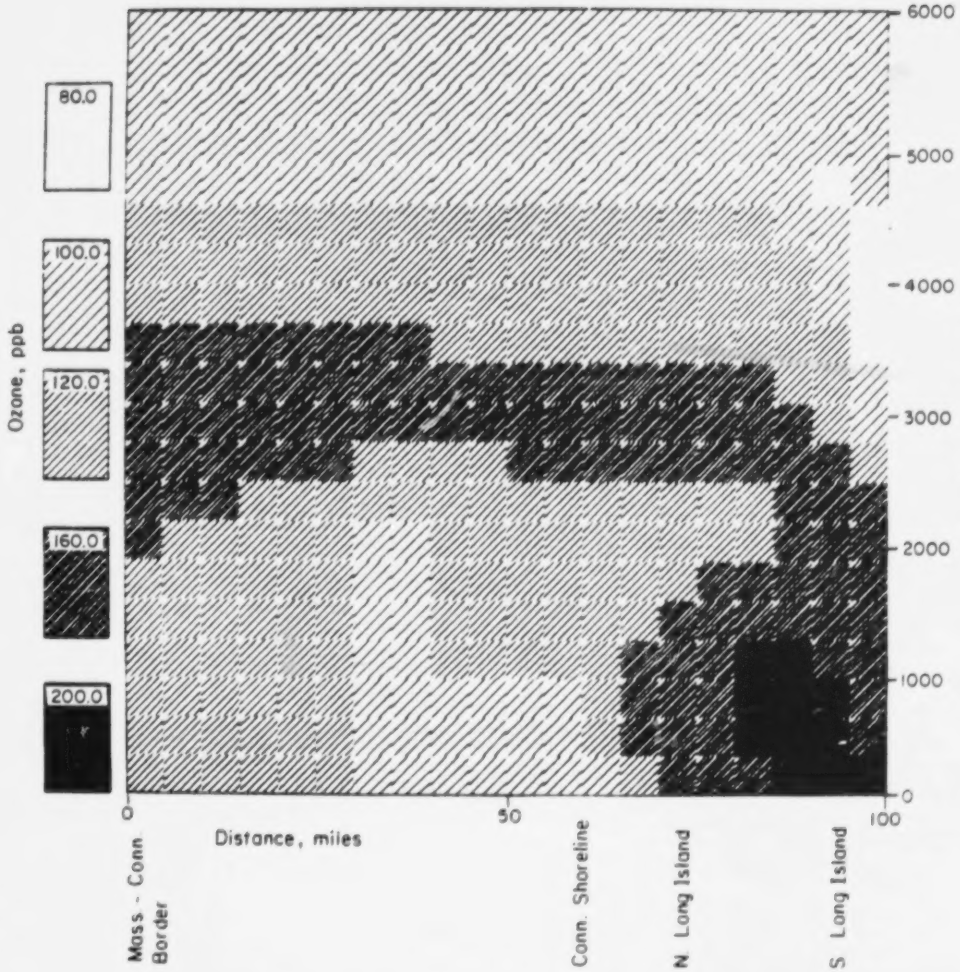


Figure 9. Ozone concentration for cross section from the Massachusetts-Connecticut border to south shore of Long Island--approximately 73° 10' longitude, August 10, 1975.

lower right corner of the figure represents the New York plume. The wind direction and the location of the flight path relative to the city are shown in Figure 10.

It is clear from the preceding figures and discussion that large cities generate well defined O_3 plumes which extend downwind of the urban center. The shape of the plume and the concentration of O_3 in the plume are dependent on meteorological and emissions factors. It seems logical that emissions from smaller cities should result in the same plume phenomenon, only on a smaller scale. The question to be addressed is whether the O_3 concentrations formed in the plumes of smaller cities are high enough to be detected unambiguously above the regional O_3 concentrations characterisitic of the Midwest. To answer this question, three flights around Springfield, Illinois, will be discussed.

Springfield is the capital of Illinois and is located near the center of the state. The census lists the population as 87,000. The area to the west and northwest of Springfield is farmland, and there are no cities of significant size for nearly 100 miles (Quincy, Illinois being the largest) in these directions. Consequently, winds from these directions are expected to exhibit the relatively low and uniform ozone concentrations necessary for this experiment. Flights around Springfield were conducted on July 12, August 1, and August 3, 1977.

Ozone Plumes from Small Cities

July 12, 1977--

Winds on July 12 were out of the southwest to west-southwest averaging 7 mph. The path of the monitoring flight around Springfield is shown in Appendix B (page B-3, Flight 2). Figure 11 displays ozone results from the flight legs perpendicular to the wind direction 10 miles upwind and 11 and 44 miles downwind of the city. Comparison of the downwind O_3 concentrations with those upwind fails to reveal a ΔO_3. The concentration is uniform between .03-.04 ppm on both sides of the city.

The lack of an ozone plume from Springfield on July 12 could be due to insufficient precursor emissions from the city or it may be that the meteorological conditions were not conducive to O_3 formation on this day. In fact, the morning of July 12 was rather overcast until 12:00-13:00 CDT,

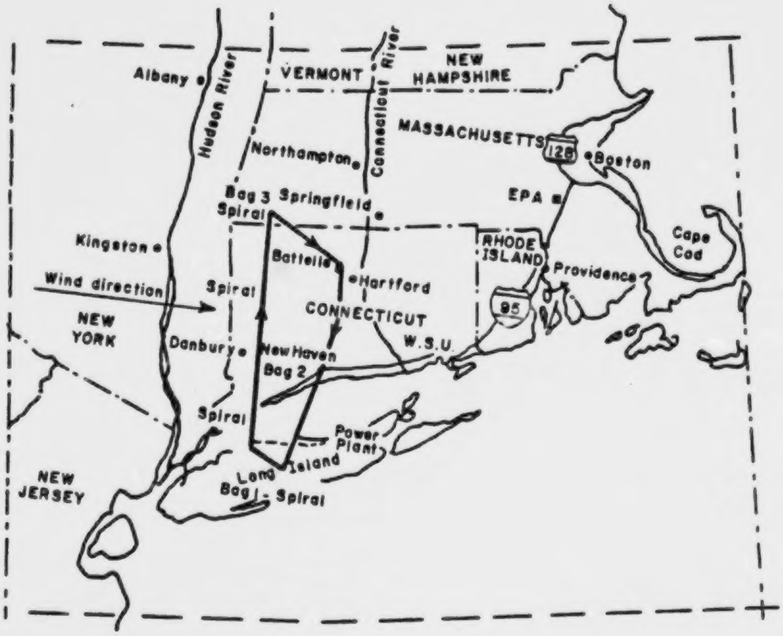


Figure 10. Ozone (in ppb) and other pollutant results for afternoon flight conducted on August 10, 1975.

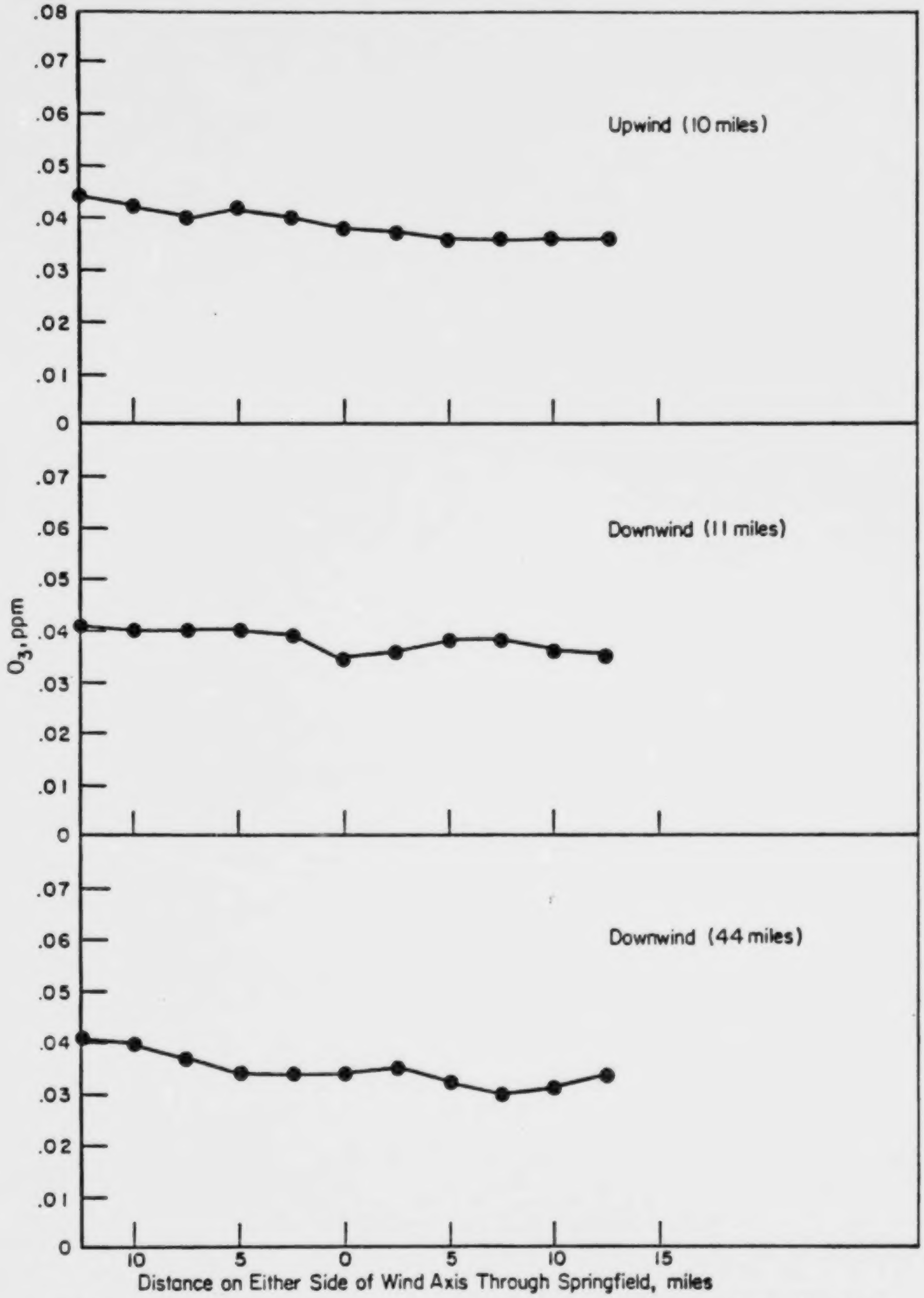


Figure 11. Ozone concentrations upwind and downwind of Springfield, Illinois, on July 12, 1977 (afternoon).

and the lack of a discernable plume may well be related to the relatively low photochemical activity during the morning hours. Ozone levels at the mobile laboratory downwind of St. Louis (at Bethalto Airport) only reached .072 ppm, suggesting that meteorological conditions were not conducive to formation of high concentrations of ozone.

August 1, 1977--

August 1, 1977 was a clear sunny day in central Illinois. Winds were from the north-northwest at 6-10 mph during the morning. Monitoring flights perpendicular to the wind direction were undertaken 9 miles upwind and 12, 33, and 65 miles downwind of Springfield. All flights were at 1000' AGL during the early afternoon. The flight pattern may be found in Appendix B (page B-25). A vertical profile upwind of the city (also shown in Appendix B (page B-58) revealed nearly uniform ozone concentrations of 40 ppb up to an altitude of 6500 feet. The O_3 data from the upwind and downwind traverses are plotted in Figure 12. The concentration upwind of the city was almost constant at 39 ppb, while the downwind levels outside the path of the Springfield plume were 34-38 ppb.

A power plant plume from a plant south of Springfield shows up clearly in the second and third downwind profiles. All three downwind profiles show a slight indication of increased O_3 directly downwind of the city, but in no case is the O_3 in the center of the plume more than 6 ppb above the concentration to the side of the plume. A ΔO_3 of 6 ppb is barely discernable in the data and is rather small compared to the 100-300 ppb ΔO_3 observed in the plumes of major cities. Nevertheless, the data do suggest that a city the size of Springfield contributes to the downwind ozone burden. The final case study, to be discussed shortly, makes an even more convincing case for such a contribution.

A comparison of the upwind and downwind ozone precursor concentrations may be found in Table 7. Only traces of reactive olefins such as propylene were observed. Aromatic hydrocarbons are not included in the comparison because data are not available for two of the traverses. Precursor concentrations are greater downwind of the city, but only marginally so. With increases in precursor concentrations downwind of the city barely detectable, it is not surprising that ΔO_3 is so small. A case in which Springfield's ozone plume is more apparent is discussed next.

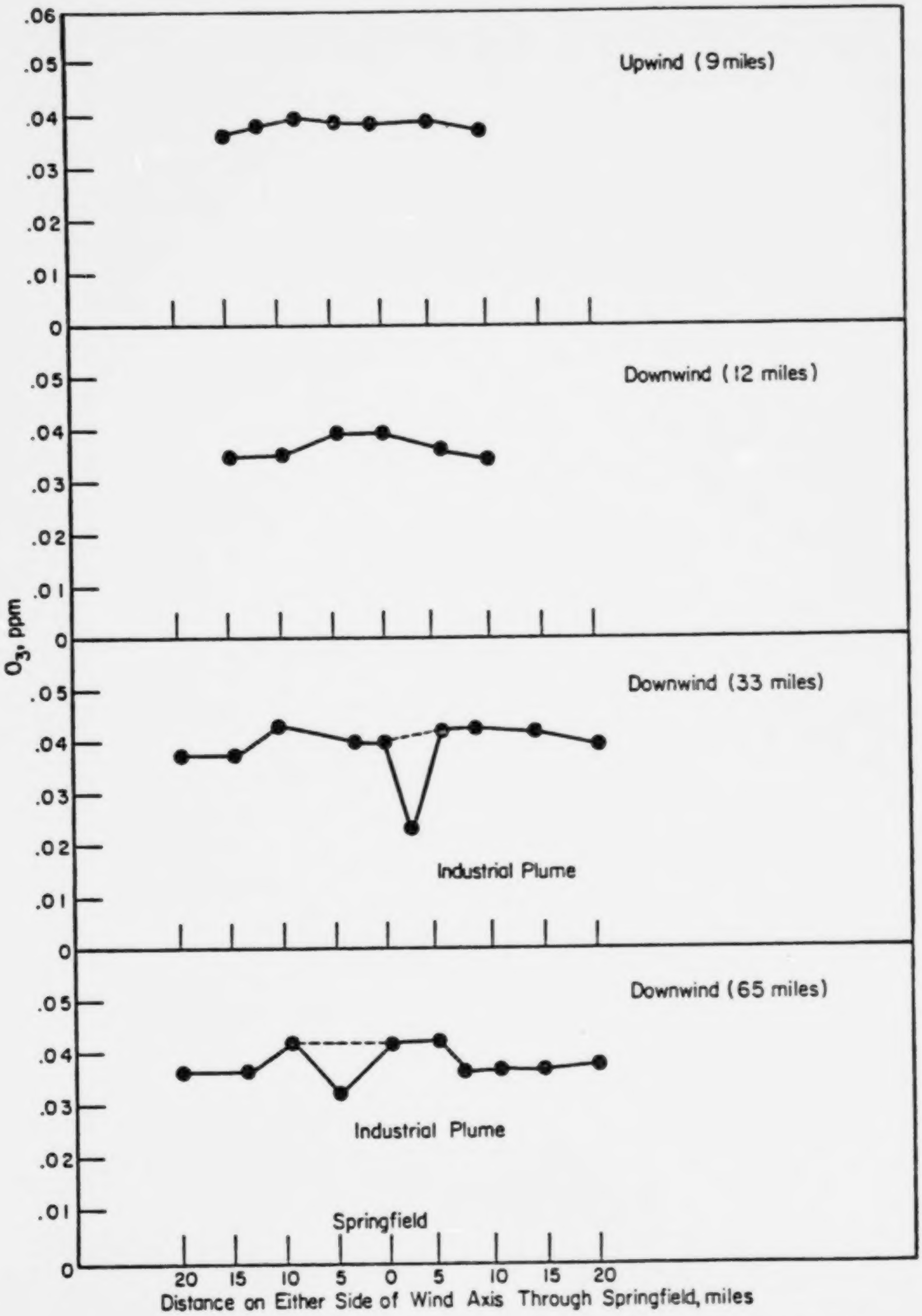


Figure 12. Ozone concentrations upwind and downwind of Springfield, Illinois, on August 1, 1977 (afternoon).

TABLE 7. UPWIND AND DOWNWIND PRECURSOR CONCENTRATION FROM FLIGHT 20, AUGUST 1, 1977 [Concentrations in ppb (NO_x) or ppbC]

	Upwind	Downwind		
	9 Miles	12 Miles	33 Miles	65 Miles
NO_x	4	5	6*	7*
ethylene	.5	.9	.6	.5
acetylene	.3	.3	.3	.4
n-butane	1.6	2.5	1.9	1.7
isobutane	3.5	4.7	3.5	3.1
isopentane	.9	1.4	1.4	1.0
n-pentane	.5	.7	.6	.6

* Estimate required subtraction of power plant plume contribution

August 3, 1977--

Clear sunny weather prevailed on August 3, with winds from the northwest at about 5 mph during most of the day. Meteorological conditions were conducive to O_3 formation since O_3 concentrations in excess of 110 ppb were observed at the mobile lab when a wind shift late in the evening transported polluted air from St. Louis to the mobile lab site in Bethalto.

The flight pattern for the afternoon of August 3 consisted of upwind and downwind traverses around Springfield. The path of Flight 23 is mapped in Appendix B (page B-30). Preflight predictions indicated westerly winds for Springfield, so north-south traverses were performed. Since the actual wind direction was northwest, the traverses cut the Springfield plume at an angle less than the desired perpendicular. This resulted in some of the traverses yielding only partial profiles of the city's plume. Results from the flight are plotted in Figure 13 for traverses 14 miles upwind and 10, 27, and 45 miles downwind of the city. The final traverse of the Springfield plume occurred on the flight back to Bethalto and is, fortuitously, perpendicular to the wind direction. All three downwind profiles show a significant increase in O_3 over upwind values, with the greatest ΔO_3 observed 27 miles downwind. With an average wind speed of 5 mph this represents a reaction time of 5 hours. The ΔO_3 at this point was nearly 30 ppb.

All downwind traverses from Flight 23 clearly show the Springfield ozone plume, and the ΔO_3 values are highly significant. It is obvious from this flight that under appropriate conditions Springfield contributes significantly to the downwind ozone burden. Comparison of upwind and downwind precursor concentrations from Table 8 suggests that the increased ozone results from precursor emissions in Springfield.

A clearer depiction of the Springfield urban plume on August 3, 1977 is shown in Figure 14. Ozone isopleths have been drawn from the afternoon flight data. Various shading densities represent ozone concentrations, as indicated in the legend. Afternoon winds were from the northwest. Plotted in this manner, the shape and dimensions of the Springfield plume are easier to distinguish. The ozone concentration in the center of the plume is in the 70-80 ppb range. While this is below the Federal standard, it is nonetheless significantly above the surrounding background levels. When one considers all the small cities and towns

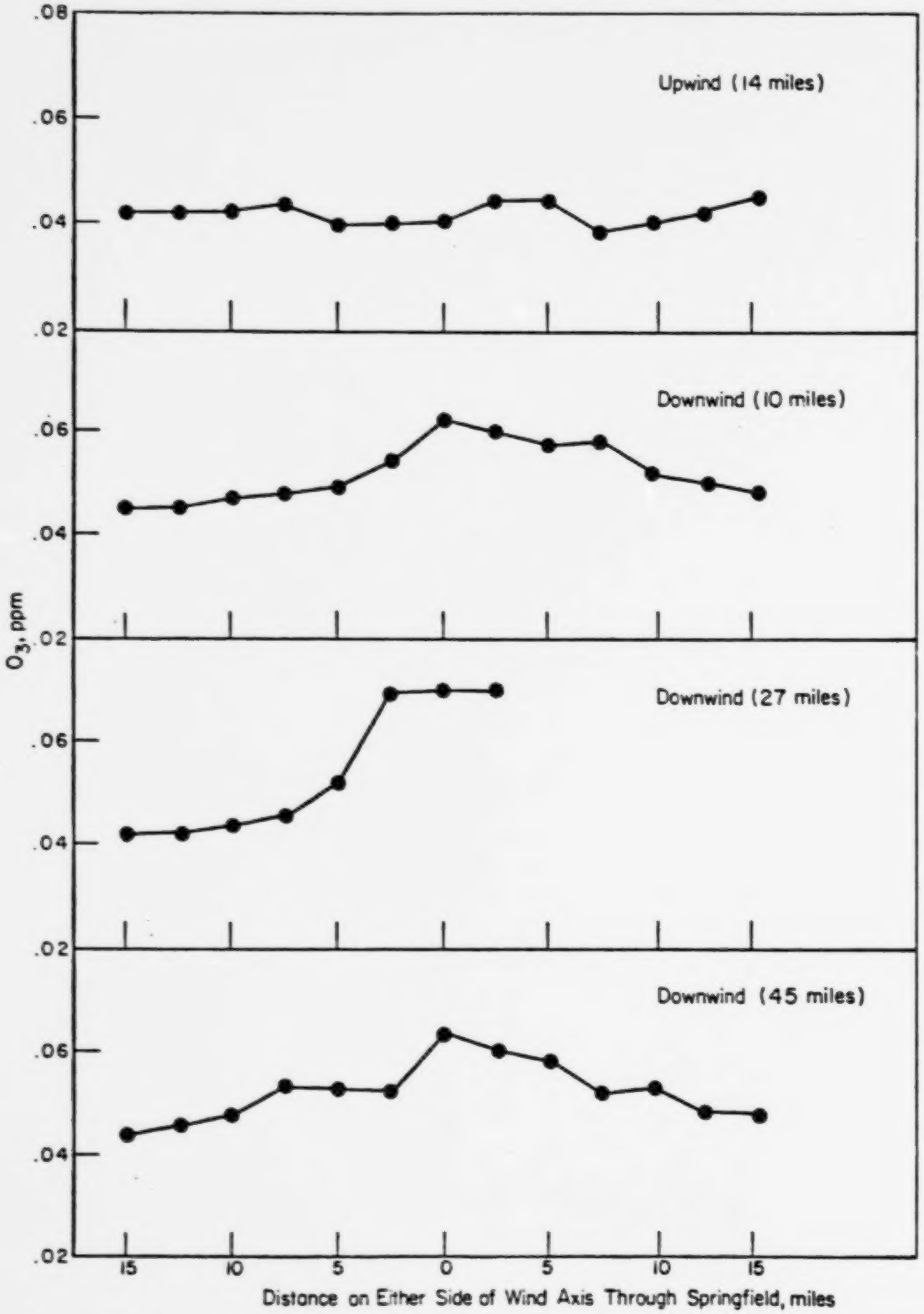


Figure 13. Ozone concentrations along upwind and downwind traverses of Springfield, Illinois, on August 3, 1977 (afternoon).

TABLE 8. UPWIND AND DOWNWIND PRECURSOR CONCENTRATIONS FROM FLIGHT 23 [Concentrations in ppb (NO_x) or ppbC]

	Upwind	Downwind		
	14 Miles	10 Miles	22 Miles	45 Miles
NO_x	7	15	12	7
acetylene	.4	.8	.4	.5
isopentane	1.6	4.0	1.6	2.3
n-pentane	.9	1.9	.9	1.1
toluene	3.1	5.6	3.5	3.5
o-xylene	3.3	7.3	4.6	4.7

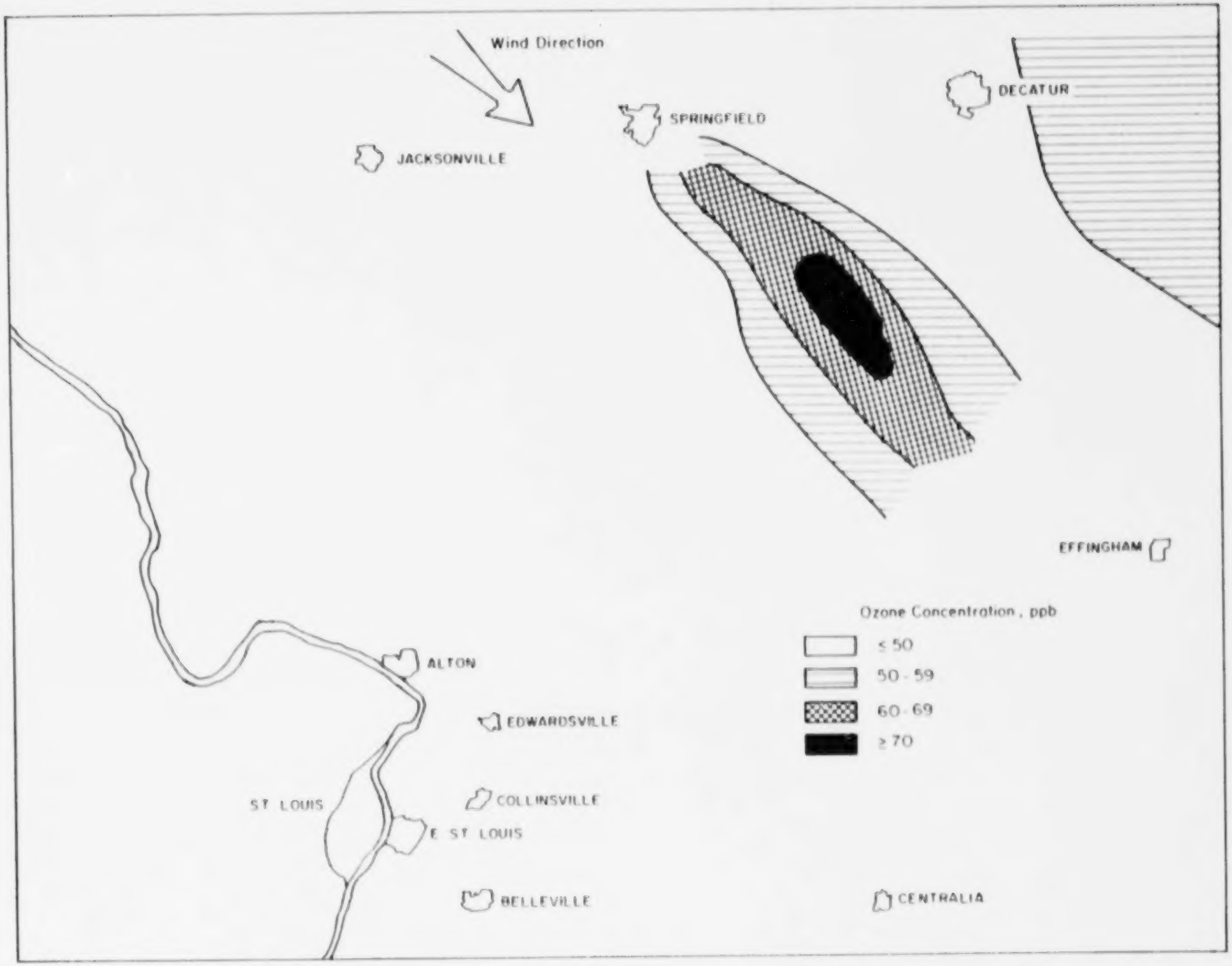


Figure 14. Ozone isopleths downwind of Springfield, Illinois, on August 3, 1977.

which contribute ozone and ozone precursors to the boundary layer, it is easier to understand why large regions of the country are occasionally blanketed by high ozone.

The conclusion to be drawn from the three Springfield plume experiments is that under conditions conducive to photochemical ozone formation, emissions from moderate size cities (populations ~100,000) lead to a definable ozone plume. These experiments demonstrate that smaller cities contribute measurably to the downwind ozone burden.

THE HIGH-PRESSURE AREA STUDY

Introduction and Summary

One objective of the program was to investigate the ozone concentrations in the air within a high pressure weather system. The methodology of the investigation was to make aircraft traverses across the high pressure system at 1000 feet above ground level with occasional spiral soundings to measure conditions at higher altitudes. The high pressure center chosen for the study moved across the eastern United States more rapidly than was anticipated. Nevertheless, the data that was gathered provided some interesting insights into the ozone concentrations above 1000 feet in relation to the position of the high pressure center and the location of urban areas. The observation of relatively high ozone concentrations at altitudes above the boundary layer led to an inquiry into the source of this ozone. Resolution of this question involved the use of three-dimensional trajectories and two tracer parameters--water vapor mixing ratio and potential vorticity. The objective of this inquiry was to learn whether this mid-tropospheric ozone had originated in the stratosphere or at the ground.

From the horizontal aircraft traverses at 1000 feet the following observations were made:

(1) At this altitude ozone concentrations within the high pressure area can be 30-40 ppb higher at the western (back) side of the high pressure area than on the eastern (leading) side.

(2) The ozone plume from urban areas is distinct on both sides of the high pressure area. It may reach concentrations as high as 40-50 ppb above background levels on the first or second day of the high pressure center's occupation of an area. However, by the third day higher concentrations pervade the entire region and the ozone concentration in the urban plume at 1000 feet may be only 15 ppb above background levels.

In the analysis of conditions above 1000 feet the information from the aircraft spiral sounding was supplemented by data from rawinsonde soundings of temperature, humidity and winds made every 12 hours by the upper air networks of the United States and Canada. These rawinsonde soundings do not measure ozone, but their measurements of other properties were used to identify layers where ozone may exist.

One source of ozone in the middle troposphere is the stratosphere. A parcel of stratospheric air entering into the troposphere through a discontinuity in the tropopause can be distinguished by its low water vapor mixing ratio (dryness) and its high potential vorticity (tendency to be both hydrodynamically stable and to move in a counterclockwise direction). The stratospheric air will move into the troposphere along an adiabatic layer and consequently can be tagged by a specific potential temperature (see definition, page 53). Using this identifier, the parcel within this layer can be checked at different places along its tropospheric path to examine the ozone content, the water vapor mixing ratio value, and the potential vorticity (see explanation, page 52).

In the middle troposphere ozone study the aircraft spiral soundings of ozone, temperature and humidity were matched with concurrent vertical variations of water vapor mixing ratio and potential vorticity obtained from the rawinsonde network. All these vertical data were displayed on special diagrams to aid in distinguishing the air parcels which were injected from the stratosphere.

Results of several sets of soundings were examined to gain an understanding of the ozone maxima which appeared in the middle troposphere. Some of this ozone is introduced by injections from the stratosphere and a cycle related to the progress of the high pressure area across the country could be hypothesized. On the soundings, ozone maxima were also observed in the lower troposphere just beneath the subsidence inversion which overlay the surface high pressure area. This ozone was traced back to the ground and apparently was generated from anthropogenic emissions.

The cold frontal surface which preceded the high pressure area was a stable layer which could be traced back to the stratosphere where an injection of ozone could possibly have occurred above the coast of British Columbia or southern Alaska. Any ozone in this injection disappeared during a seven-day trip from the tropopause along the Pacific Coast at about 25,000 feet to the ground in central Illinois where the Battelle aircraft conducted its initial sounding.

The injection of stratospheric air into this stable layer coincided with the time when a transient low pressure center at 500 millibars (about 18000 feet) moved into the position of the semi-permanent low pressure trough located above the northwestern United States at this altitude. The juxtaposition of the two low pressure areas coincided with the occurrence of a minimum tropopause height. As the transient low pressure moved on across southern Canada, several other injections of stratospheric air occurred at heights higher than the original injection on the coast. These injections could be traced as dry stable layers descending in the atmosphere. They were measured by the spiral soundings in the middle troposphere and contained high concentrations of ozone. As these stable layers moved eastward within the high pressure area, they lost their dryness and became less stable. It seems probable that in the air above the backside of the high, the layers containing elevated ozone still are contiguous, but they no longer have the identifying characteristic of stratospheric air--low water vapor mixing ratios and high potential vorticities. It is also possible that this ozone can be mixed uniformly within the middle troposphere and that eventually, some of this well-mixed ozone could descend to the ground at a concentration considerably less than that which it had when it left the stratosphere.

The Study

On Thursday July 21, 1977, a cold front passed across Illinois from northwest to southeast and by Friday a large high pressure area was moving across the Great Lakes region on its way to the Atlantic Ocean where the center of the high crossed the Maryland-Virginia coast between Saturday and Sunday. During the period of Friday July 22 to Sunday July 24 measurements by both the Battelle and Washington State University aircraft were devoted to the study of conditions in the high pressure area. Measurements of ozone, ozone precursors, and meteorological parameters at about 1000 feet AGL were made on cross country flights covering the mideastern United States (Figure 15). Several bag samples were collected for later analysis and spiral soundings were made at nine locations along the route. Additional descriptive material regarding the flights and soundings is presented in Table 9.

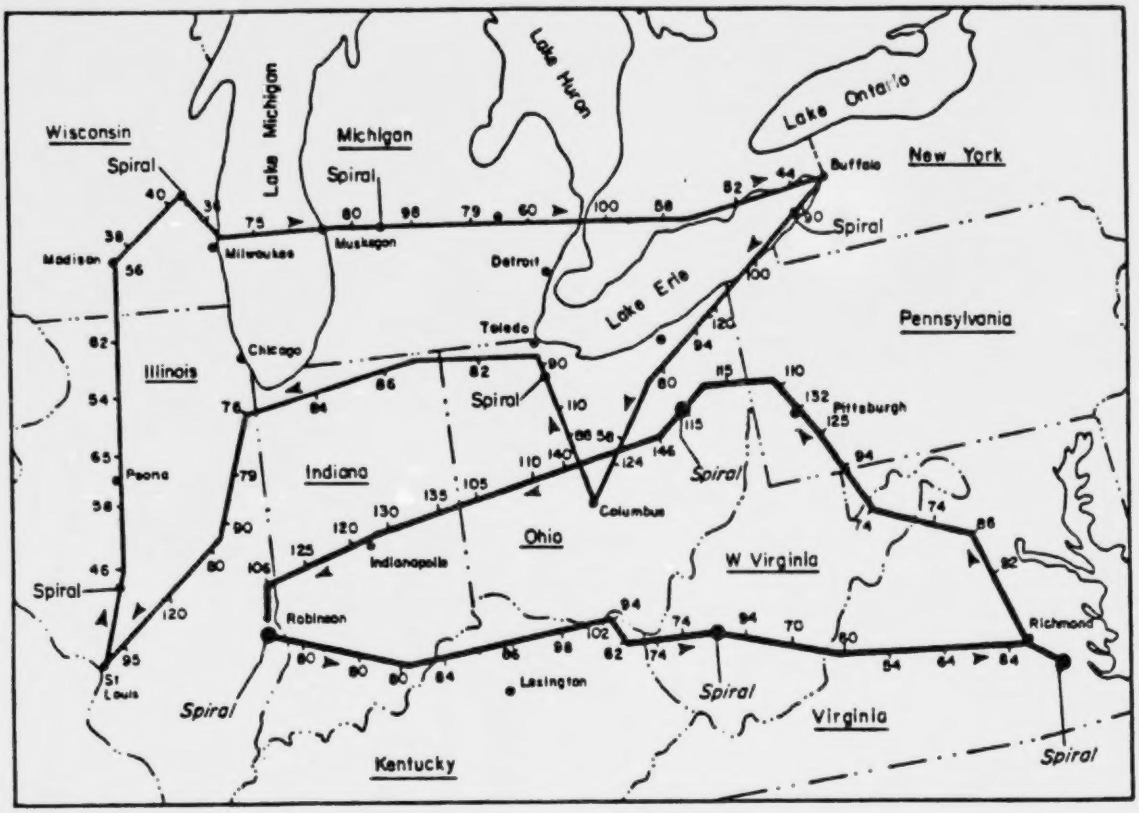
Findings

Meteorological Situation--

Figures 16 through 22 are the seven daily weather maps prepared by the National Oceanic and Atmospheric Administration for the period July 18-24, 1977. This series depicts the sequence of weather system movements at the surface and also in the upper air during the time of the cross-country flights. One day's maps consists of (1) the surface weather map (top) for 7:00 a.m. EST (08:00 EDT and 07:00 CDT), (2) the 500-millibar chart (lower left hand map) with height contours in feet and temperatures in degrees Celsius for 7:00 a.m. EST, (3) the highest and lowest temperatures in degrees Fahrenheit for the previous day (lower right center map) and (4) the areas (black) where precipitation was recorded during the previous day (lower right hand map).

From the surface weather map one can determine such pertinent information as locations of high pressure centers, locations of fronts, and winds at the weather stations. A station with a circle around it denotes calm conditions for the 07:00 CDT weather observation. Interest in the 500 mb chart is centered on the location of low centers and troughs (areas where contours dip southward). Large areas devoid of precipitation on the precipitation map will frequently match areas covered by high pressure centers on the previous day's 07:00 surface weather map.

From July 18 to July 20 the surface pressure pattern over the seven states bordering the lower Great Lakes did not change. The region was in the rear of a high pressure area. Winds were southwesterly or calm on the 07:00 CDT map, maximum temperatures were in the 90's, and precipitation was scattered. Haze or fog was reported at many of the stations at



WSU Flights:

Sat.	7/23	Robinson to Richmond	1130 CDT to 1700 CDT
Sun.	7/24	Richmond to Robinson	1130 EDT to 1740 EDT

BCL Flights:

Fri.	7/22	Bethalto to Muskegon	1000 CDT to 1608 CDT
Sat.	7/23	Muskegon to Columbus	1400 EDT to 2040 EDT
Sun.	7/24	Columbus to Bethalto	0845 EDT to 1415 EDT

Figure 15. Ozone concentrations (ppb) along the paths of the Washington State University and Battelle's Columbus Laboratories cross-country flights between July 22 and July 24. (Sites of spiral soundings are shown.)

TABLE 9. BATTELLE AIRCRAFT SPIRAL SOUNDINGS MADE DURING HIGH PRESSURE AREA STUDY -- 1977

Sounding Number	Sounding Date	Sounding Period	Location (nearest city)	Minimum Altitude (feet)	Maximum Altitude (feet)	Nearest NOAA Rawinsonde Station	Flight Period
8-1	Friday July 22	10:30-11:00 CDT	Springfield Ill.	3,000	12,000	Peoria, Ill.	10:00-1608 CDT
8-2	Friday July 22	14:30-15:00 CDT	Fond du Lac, Wisc.	3,000	20,000	Green Bay, Wisc.	10:00-1608 CDT
9-1	Saturday July 23	15:00-15:30 EDT	Grand Rapids, Mich.	2,000	12,000	Flint, Mich.	14:00-20:40 EDT
9-2	Saturday July 23	19:00-19:30 EDT	Erie, Pa.	2,000	20,000	Buffalo, NY	14:00-20:40 EDT
10-1	Sunday July 24	09:30-10:00 EDT	Toledo, O	3,000	12,000	Flint, Mich	08:45-14:15 EDT

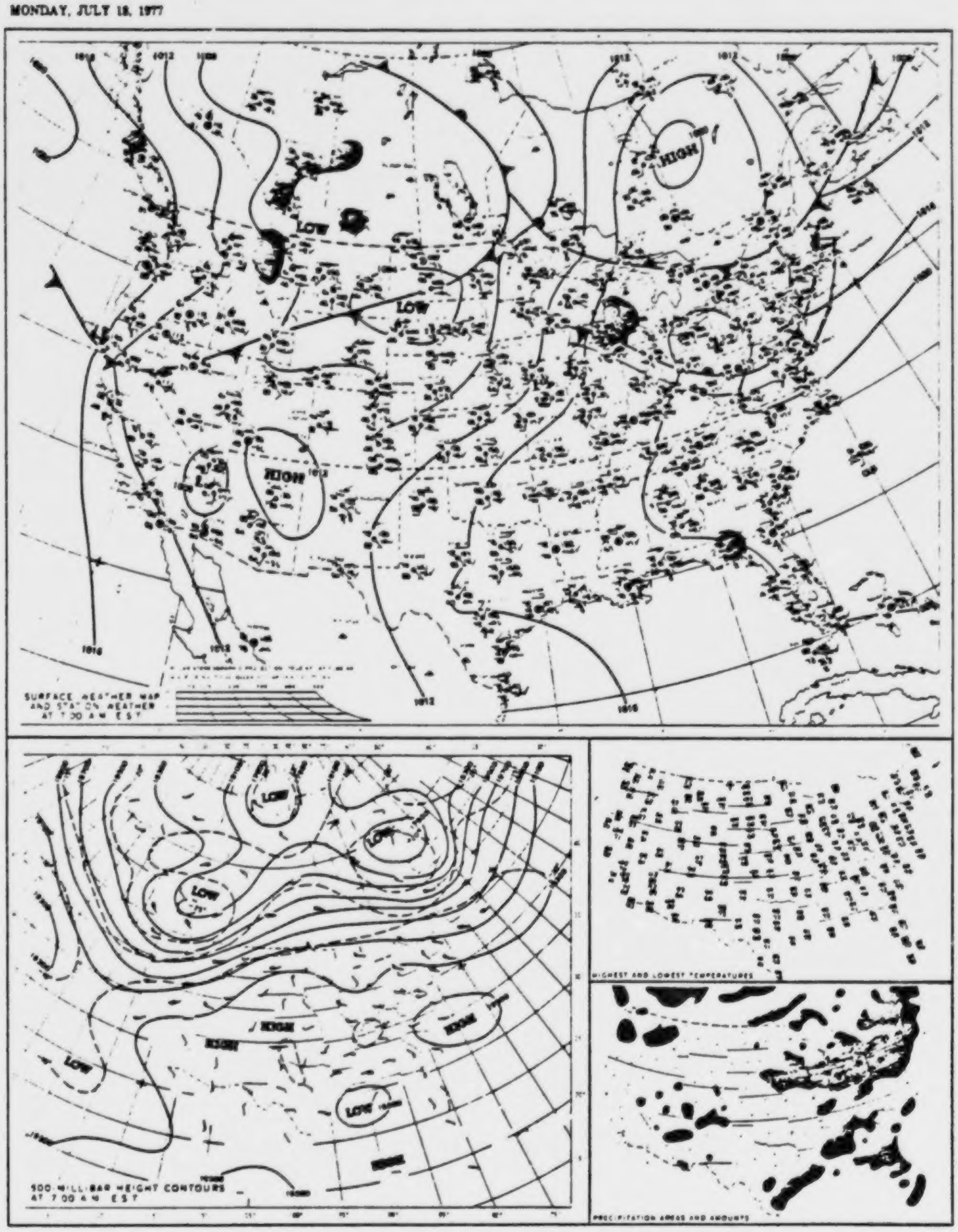

MONDAY, JULY 18, 1977
LOW
LOW
HIGH
HIGH
LOW
1012
1016
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. EST
LOW
LOW
LOW
LOW
HIGH
HIGH
HIGH
LOW
500-MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. EST
HIGHEST AND LOWEST TEMPERATURES
PRECIPITATION AREAS AND AMOUNTS

Figure 16. Daily weather map for July 18, 1977.

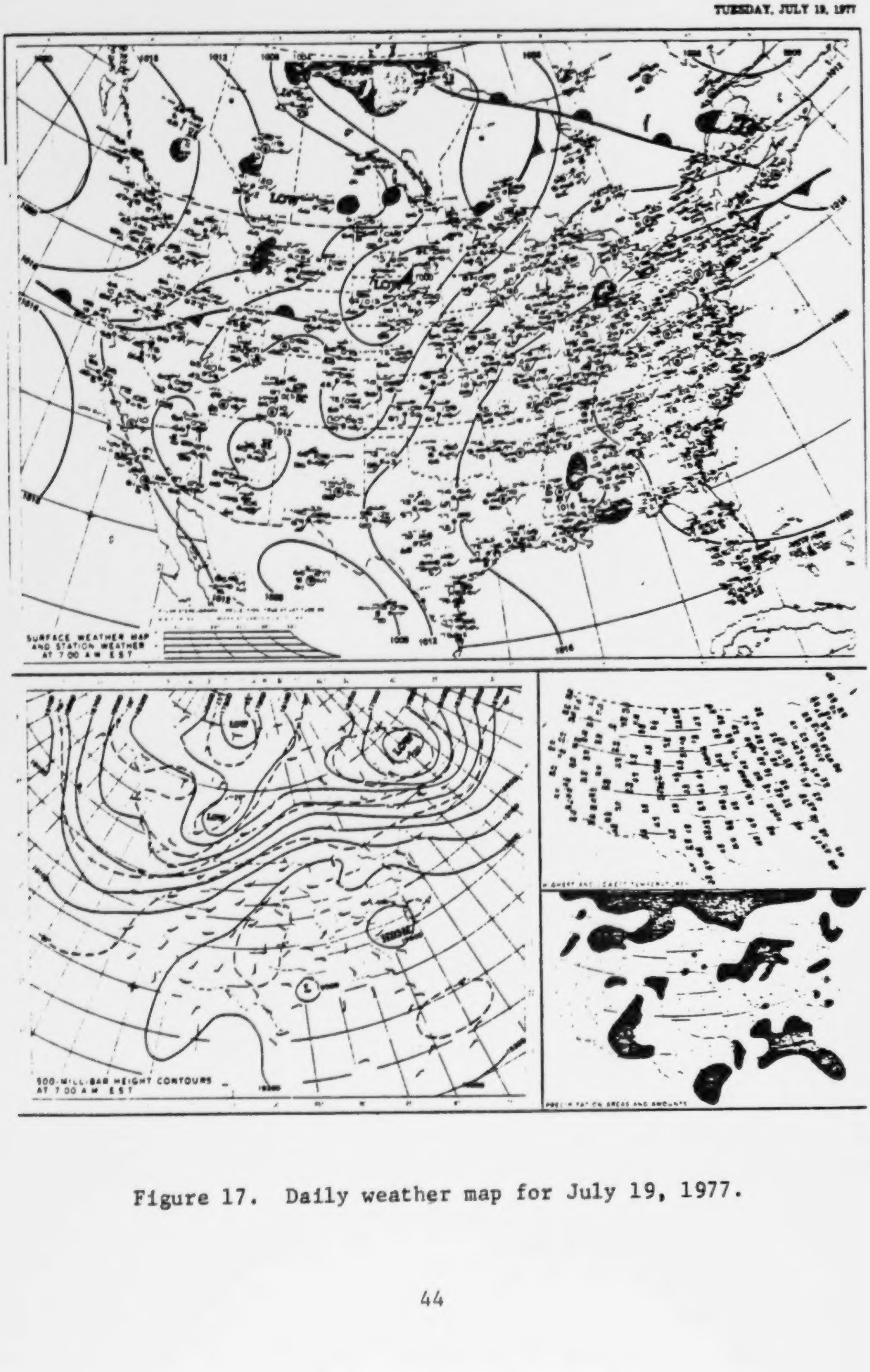

TUESDAY, JULY 19, 1977
LOW
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
LOW
LOW
500-MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. E.S.T.
PRECIPITATION AREAS AND AMOUNTS

Figure 17. Daily weather map for July 19, 1977.

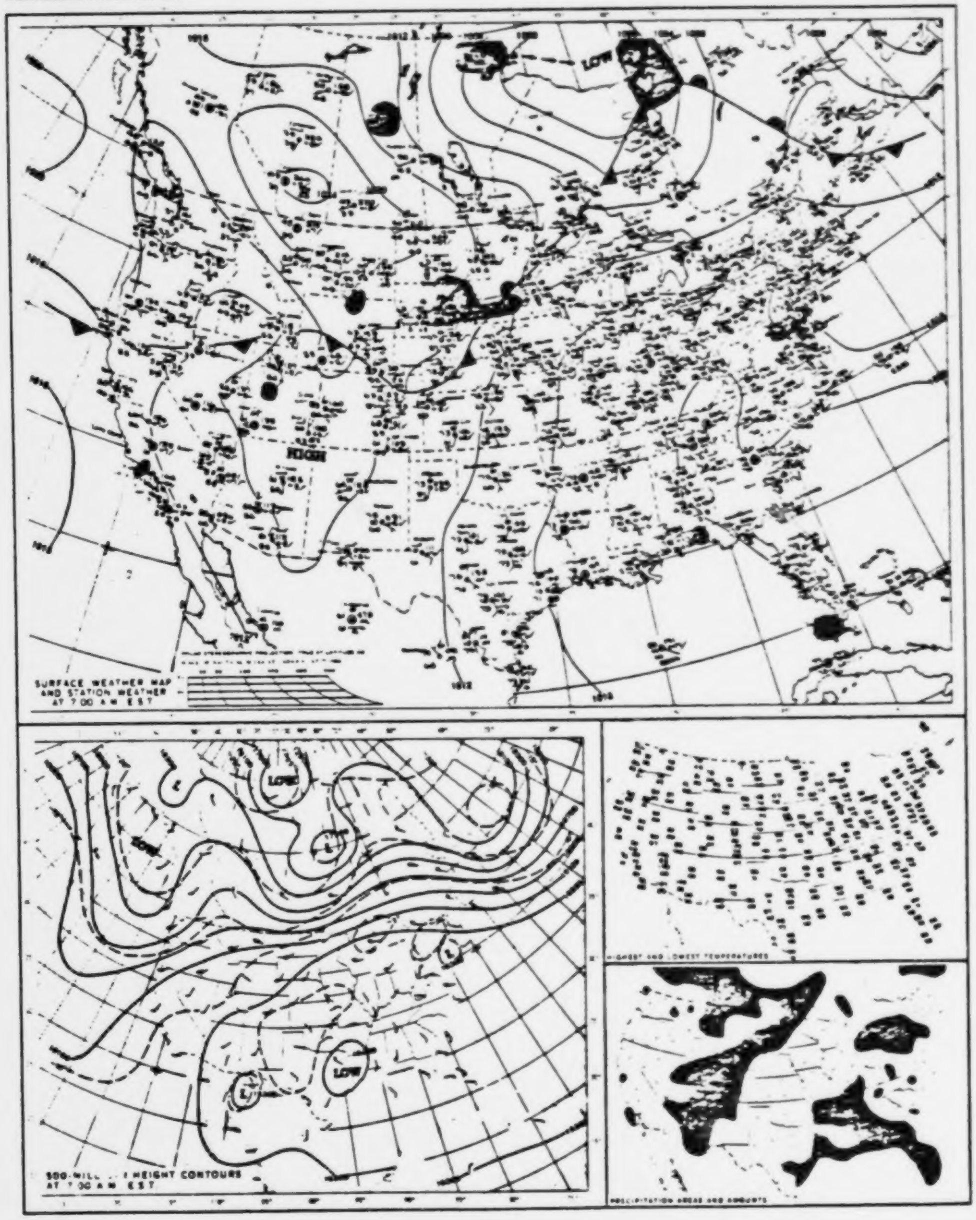

WEDNESDAY, JULY 20, 1977
LOW
HIGH
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
LOW
LOW
500-MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. E.S.T.
HIGHEST AND LOWEST TEMPERATURES
PRECIPITATION AREAS AND AMOUNTS

Figure 18. Daily weather map for July 20, 1977.

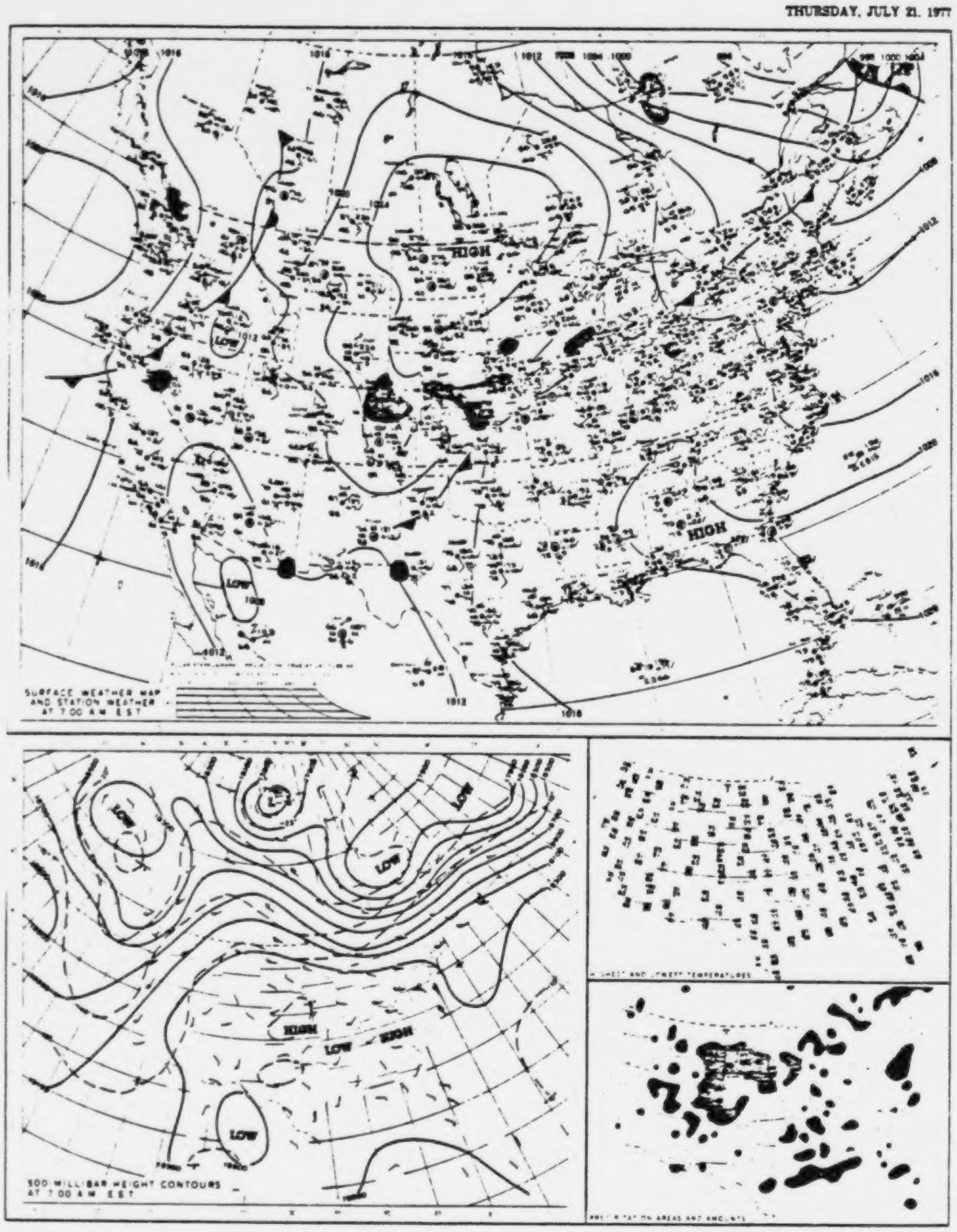

THURSDAY, JULY 21, 1977
HIGH
LOW
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
LOW
LOW
LOW
HIGH
LOW
HIGH
LOW
500 MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. E.S.T.
HIGHEST AND LOWEST TEMPERATURES
PRECIPITATION AREAS AND AMOUNTS

Figure 19. Daily weather map for July 21, 1977.

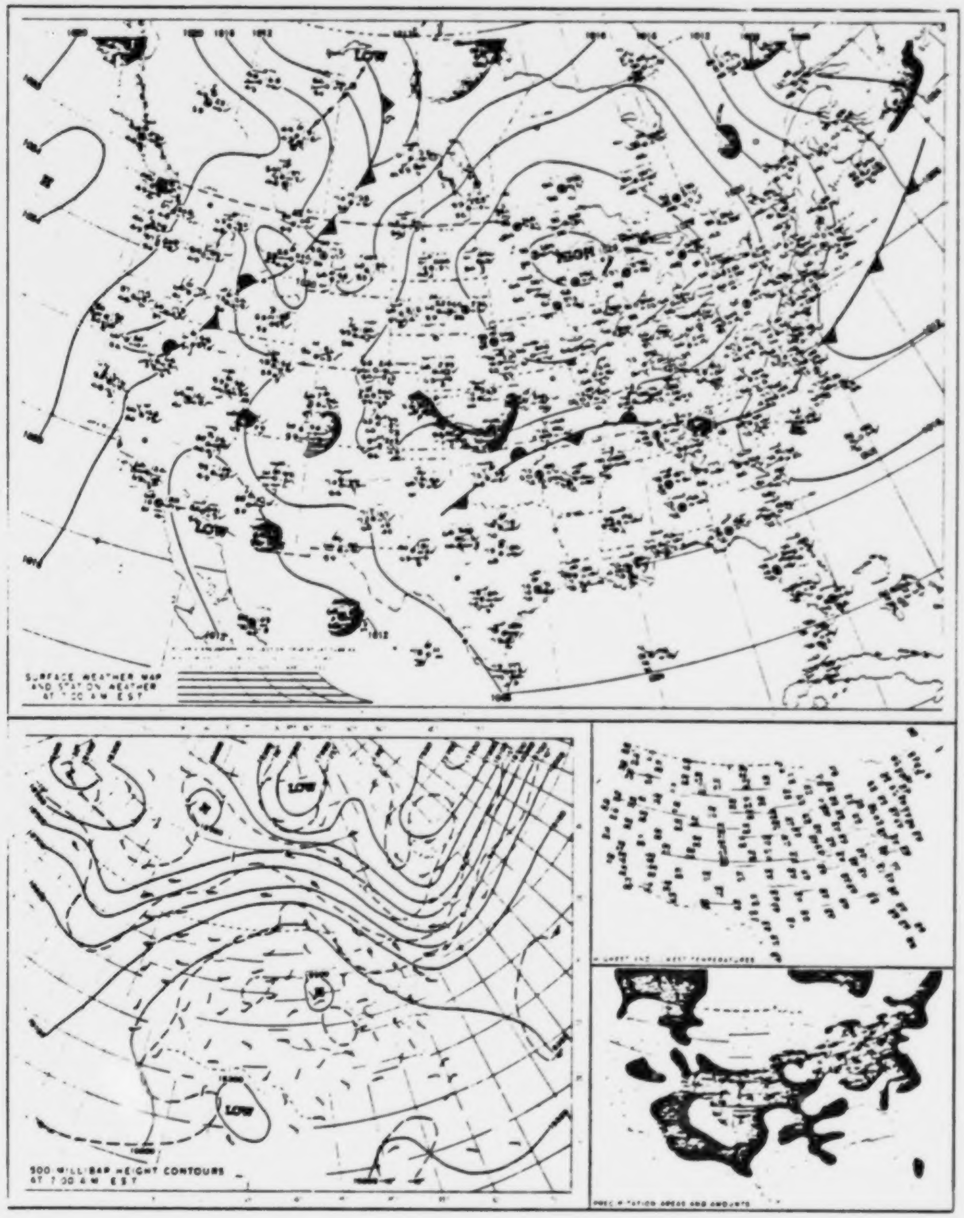

FRIDAY, JULY 22, 1977
LOW
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
LOW
LOW
500 MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. E.S.T.
HIGHEST AND LOWEST TEMPERATURES
PRECIPITATION AREAS AND AMOUNTS

Figure 20. Daily weather map for July 22, 1977.

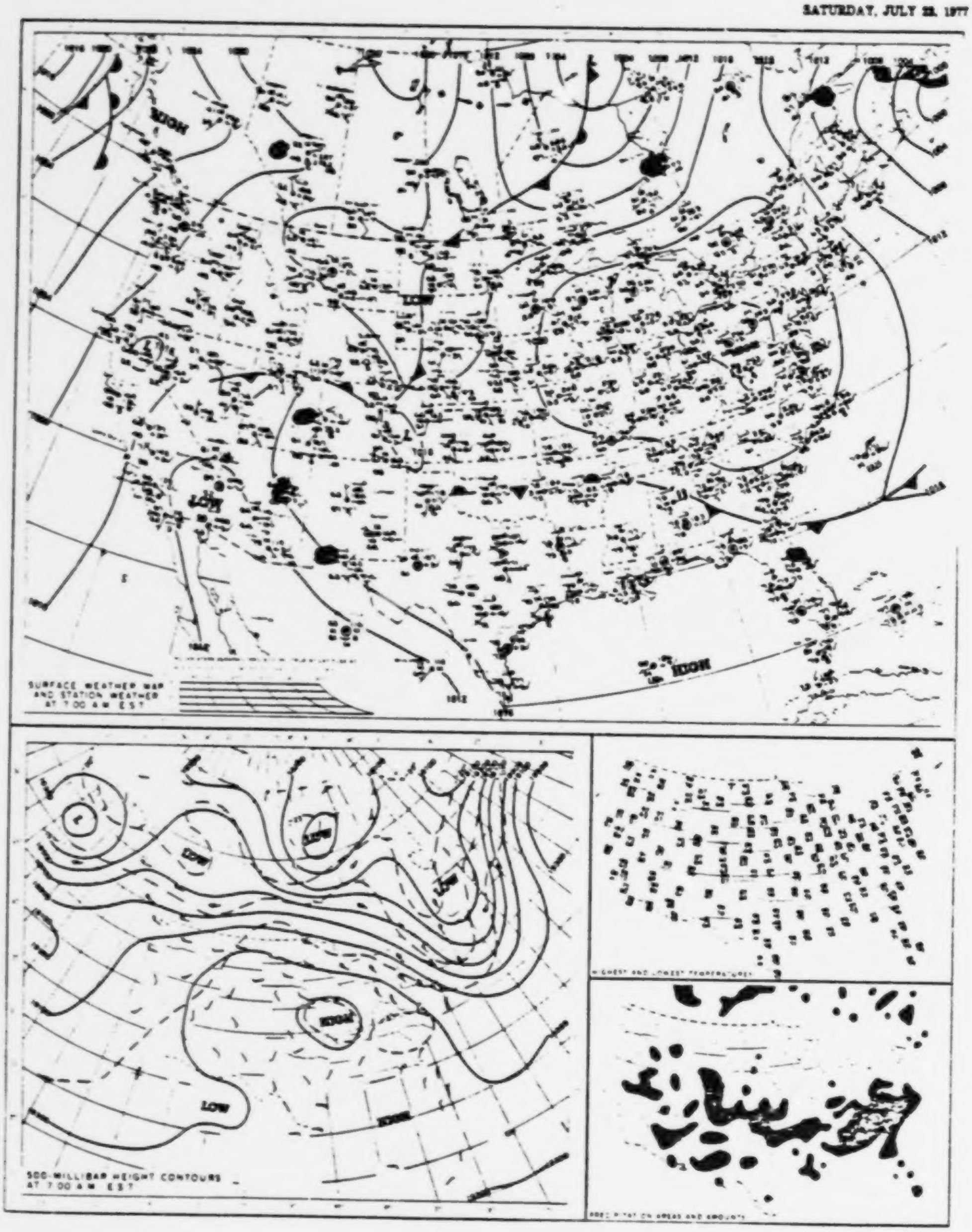

SATURDAY, JULY 23, 1977
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
500-MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. E.S.T.
HIGHEST AND LOWEST TEMPERATURES
PRECIPITATION AREAS AND AMOUNTS

Figure 21. Daily weather map for July 23, 1977.

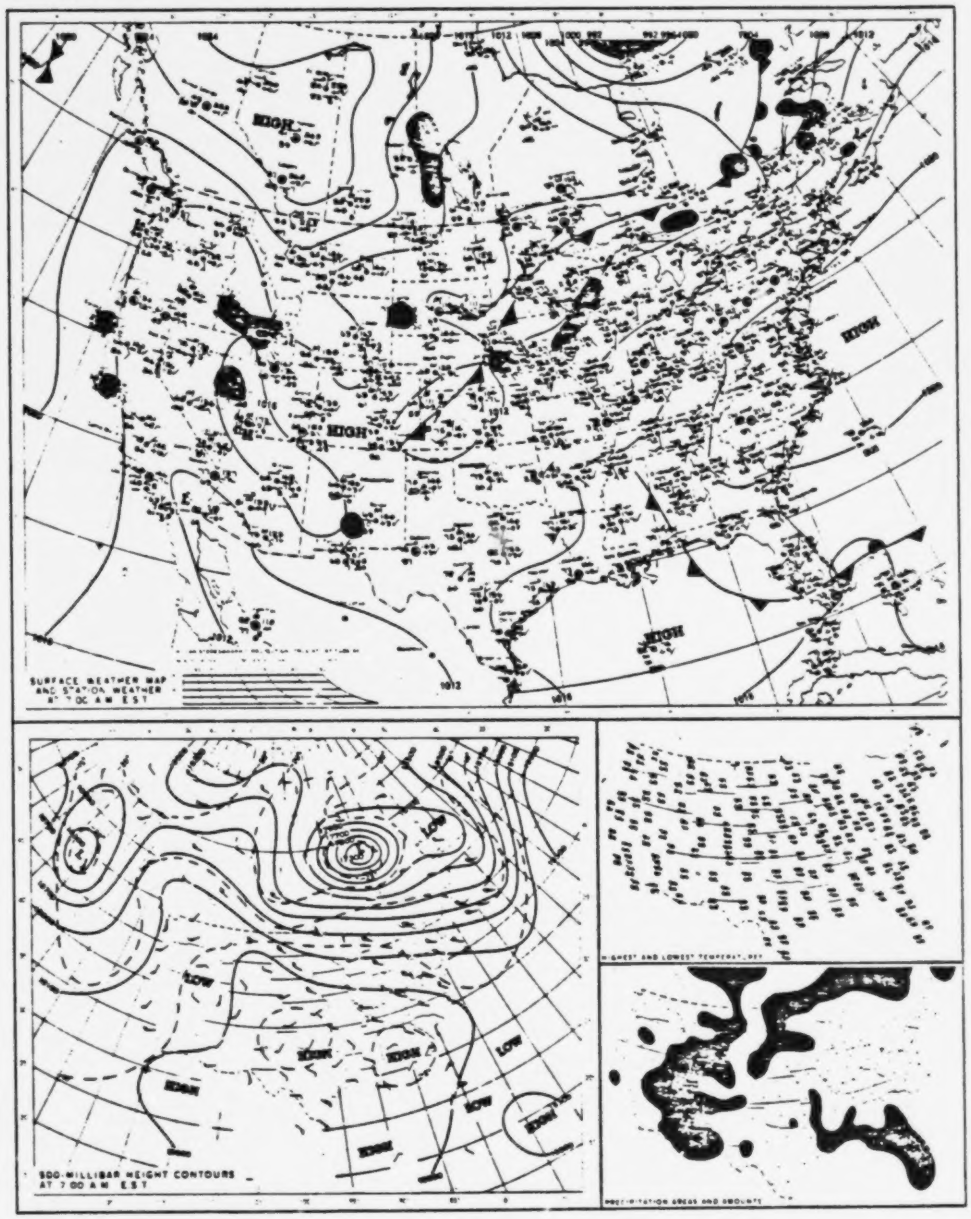

SUNDAY, JULY 24, 1977
HIGH
HIGH
HIGH
HIGH
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. EST
LOW
LOW
HIGH
HIGH
LOW
HIGH
LOW
HIGH
HIGH
500-MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. EST
HIGHEST AND LOWEST TEMPERATURES
PRECIPITATION AREAS AND AMOUNTS

Figure 22. Daily weather map for July 24, 1977.

07:00 CDT. A front across the northwestern United States showed little movement; however, a distinct high pressure area did develop behind it by Wednesday July 20.

At 500 mb a small trough moved from the large semi-permanent trough in the Pacific Ocean eastward from British Columbia, across Alberta, and into northern Saskatchewan. During the next three days this 500 millibar trough continued moving eastward and on July 23 it had helped produce a deep trough along the North Atlantic coast. Between July 20 and July 24 the cold front and the high pressure area behind it moved quickly across the eastern United States. The high pressure center moved from southern Alberta on July 20, to northern Minnesota on July 21, to northern Wisconsin on July 22 and to West Virginia on July 23. By July 24 it was off the Virginia coast and another cold front was entering the Great Lakes region.

Measurements of wind direction, temperature, and humidity at Battelle's Bethalto, Illinois station and at the St. Louis airport indicate that the front which was across northern Illinois on the morning of July 21, passed through the St. Louis region at about 18:00 CDT. Thunderstorms occurred in the area at this time. At Bethalto the ozone concentration, which had reached its daily maximum of 116 ppb at 15:00 CDT, dropped from 93 ppb to 75 ppb between 17:00 and 18:00 and continued to fall until midnight.

Cross Country Flights--

Between Friday morning and Sunday evening, both the Battelle and Washington State University airplanes made cross country flights across the high pressure area from west to east and back. Battelle's aircraft flew from Bethalto to Muskegon, Michigan, on July 22, then to Columbus, Ohio, on July 23, and returned to Bethalto on July 24. The Washington State cross country flights were from Robinson, Illinois to Richmond, Virginia, along a southern route on July 23 with a return to Robinson by a more northerly route the following day.

Ozone concentrations measured at about 1000 ft AGL along these flight paths are shown in Figure 15. On Friday, July 22, no concentrations above 100 ppb were observed on the Battelle flight which traversed a path slightly to the rear of the high pressure center.

During its Saturday afternoon flight, the Washington State aircraft's highest measured ozone concentration was 102 ppb on the Ohio-Kentucky border. Later that day, the Battelle flight traversed areas of greater than 100 ppb concentrations northeast of Detroit, northeast of Cleveland-Erie, and northeast of Columbus, directions which were downwind of these cities since they were on the northwest side of the high pressure center.

By the following day, the movement of the high pressure center had slowed considerably. The Battelle flight on this day began at 08:45 EDT at Columbus and ended at about 16:00 EDT at Bethalto. During the flight, only two areas of plus 100 ppb concentrations were observed--in the morning over northwestern Ohio and in the afternoon northeast of St. Louis. The morning ozone must have been preserved from the preceding day; however, the afternoon maximum can be attributed to transport from St. Louis along the trailing edge of the high pressure area.

The Washington State flight on this date was almost entirely in the afternoon. After this aircraft entered western Pennsylvania, ozone measurements at 1000 feet never dropped below 100 ppb for the remainder of the flight across central Ohio and Indiana. Taking into consideration the concentrations observed in the pre-noon portions of both flights on this date, it is reasonable to assume that the entire area from Washington, D.C. to St. Louis, on the rear of the high pressure area, was submerged in ozone concentrations between 100 and 150 ppb with the maximum concentrations lying above eastern Ohio. There were some indications of city plume effects downwind of the larger cities, but the plus 100 ppb concentrations pervaded rural as well as urban areas.

Atmospheric Soundings--

Air with high ozone concentrations has been observed to occur in contiguous volumes or clouds within that part of the troposphere lying between the boundary layer (approximately 3000-5000 feet above mean sea level) and the tropopause (approximately 25,000-35,000 feet above mean sea level in mid latitudes). Singh, Johnson, Ludwig, and Viezee (8,9,10) have reported on several field investigations of upper - tropospheric ozone. They concluded that the stratosphere is the major source for this trospheric ozone. Their work suggests that O_3 of stratospheric origin descends into the troposphere and is found at altitudes as low as 8000 feet. When cyclones form or intensify intermittently in an upper tropospheric trough, an injection of stratospheric air into the troposphere occurs. The point of injection is at a break in the tropopause below and to the north of the jet stream. From this point the stratospheric air proceeds generally downward and southward. This contiguous volume of air is 100-300 km wide and several hundred km long. Johnson and Viezee(9) state that this stratospheric ozone may reside in the troposphere for up to four months during which time it is dissipated by tropospheric mixing, surface-based mixing, precipitation scavenging, and deposition to the ground.

In an investigation of unusually high ozone concentrations at a surface station, Lamb(11) employed two meteorological parameters frequently used in stratospheric/tropospheric exchange studies--water vapor mixing ratio and potential vorticity--to demonstrate that the ozone had originated in the stratosphere. Low values of water vapor mixing ratio and high values of potential vorticity are typical of stratospheric air that is residing in the troposphere.

It is easy to understand that low values of water vapor mixing ratio indicate dry air and that air from the relatively moisture-free stratosphere would be dry in comparison with typical tropospheric air. Potential vorticity, however, is not a familiar parameter. A few paragraphs will be provided here for those who are interested in a discussion of potential vorticity and why high values of this parameter are found in stratospheric air which has been injected into the troposphere.

Potential Vorticity--

Vorticity is a measure of rotation in fluid flow. Absolute vorticity is the sum of the vorticity relative to the earth (V = relative vorticity) and the vorticity of the earth itself as it rotates on its axis (f = Coriolis parameter). Relative vorticity can be written as

$$V = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

in x-y coordinates where v is velocity in the y direction and u is velocity in the x direction. In a coordinate system based on the direction of flow of an air parcel, the relative vorticity can be expressed as

$$V = \frac{\partial c}{\partial n} - c\,\frac{\partial \alpha}{\partial s}$$

where s is the direction along the flow, n is the direction perpendicular to the flow (positive to the right of the flow), c is the speed of the flow, and α is the angle (positive in a clockwise direction) between the direction of flow at an initial point and at a point downstream.

Positive vorticity in the northern hemisphere is counterclockwise rotation (cyclonic flow). In the x-y coordinate system, increasing southernly winds as one proceeds to the east ($\frac{\partial v}{\partial x}$ positive) would cause a parcel of air to be rotated counterclockwise. Similarly, counterclockwise rotation along the y axis (northward direction) would occur with a decrease in easterly winds along this axis ($\frac{\partial u}{\partial y}$ decreasing or $-\frac{\partial u}{\partial y}$ increasing).

The jet stream blows from west to east in the northern hemisphere. An air parcel just north of the jet stream is subjected to a strong counterclockwise rotation. Injections of air from the stratosphere into the troposphere occur at the tropopause-break area which coincides with the jet stream position. The injected air originates north of the jet stream in the stratosphere and passes beneath it into the troposphere. This air retains its high positive vorticity.

In hydrodynamic theory potential vorticity is defined as the product of the absolute vorticity and the stability

$$P = -\frac{\partial \Theta}{\partial p}(\zeta + f) \quad .$$

The term $-\frac{\partial \Theta}{\partial p}$ is a measure of stability.

In a stable atmosphere the potential temperature,[*] Θ, as measured from a rising balloon would increase with height. In other terms, it increases with decreasing atmospheric pressure, p, as one goes upward in the atmosphere.

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[*] In meteorology potential temperature (denoted by Θ) is the temperature a parcel of dry air would have if brought adiabatically from its initial pressure to the standard pressure of 1000 millibars. Thus the potential temperature measured within a parcel of air would remain constant if the parcel ascends or descends in the atmosphere without heat transfer and without condensation of the water vapor in the parcel.

Thus, in a stable atmosphere, $-\frac{\partial \Theta}{\partial p}$, would be positive. There is a high rate of increase of Θ with height above the tropopause, thus, the value of $-\frac{\partial \Theta}{\partial p}$ is positive and relatively large.

From hydrodynamic theory it can also be shown that in dry adiabatic motion the potential vorticity of an air parcel remains constant (conservation of potential vorticity). In meteorology, dry adiabatic motion is considered to be isentropic motion, that is, motion in which the potential temperature remains constant. For many purposes motion in the free atmosphere over periods of two days or less is assumed to be adiabatic. The conservation of potential vorticity on an isentropic (constant potential temperature) surface is written mathematically as

$$P_{\Theta} = -\frac{\partial \theta}{\partial p}(\zeta_{\partial} + f)_{\theta} = \text{constant}$$

In practice, the stability $(-\frac{\partial \theta}{\partial P})$ of the parcel is an average of the stability in a layer extending about 0.5 km on either side of the surface.

Air injected from the stratosphere into the troposphere would have relatively high positive values of stability $(-\frac{\partial \theta}{\partial p}$ and absolute vorticity (L + f) and thus, the product of these two terms (potential vorticity) would be higher within the encroaching stratospheric air than within the surrounding tropospheric air. As long as the dry adiabatic motion of the stratospheric air is not disturbed, the difference in potential vorticity between the injected stratospheric air and the ambient tropospheric air is quite marked. Over longer periods of time (e.g. more than two days) the potential vorticity of the injected air can be expected to decrease as mixing with the tropospheric air takes place. However, the potential vorticity values of the air which originated in the stratosphere may still be sufficiently greater than those in the ambient air to still identify it as stratospheric air.

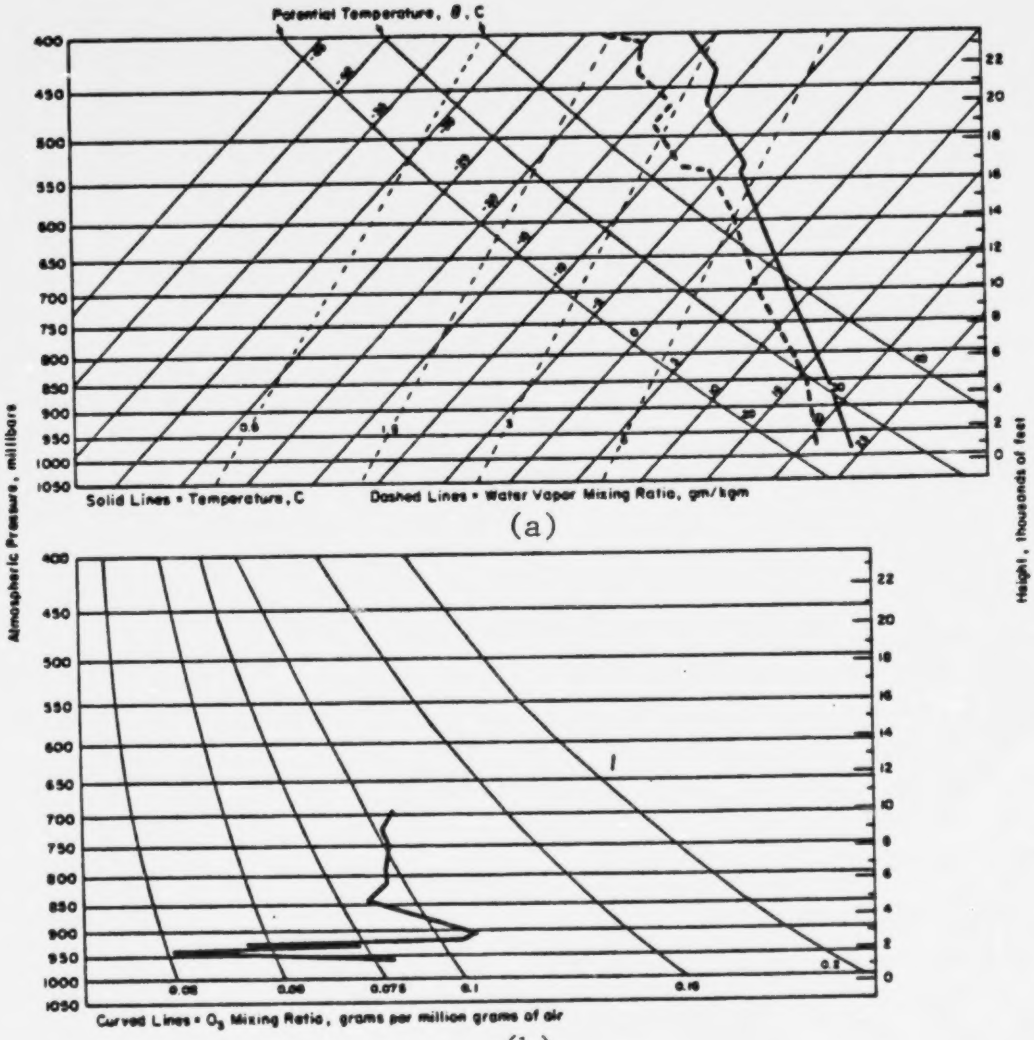
Measurement and Data Display Methods--

Upper atmospheric temperatures, humidities, and winds as measured by balloon-borne rawinsondes are used routinely in the preparation of weather forecasts. A single sounding reveals considerable detail about the structure of the atmosphere above a station, specifically, the height of temperature inversions and other stable layers and whether these layers are moist or dry. By considering the soundings made concurrently at several nearby stations one can discern the horizontal extent of these stable layers and whether they slope from one point to another. When consecutive soundings at one station or at a network of stations are compared, the movement of the stable layers can be determined. The slope and movement of a frontal surface, one type of stable layer, can be ascertained by inspecting the plots of temperature versus height from several rawinsonde stations. Plotting the soundings on special adiabatic diagrams can aid in the analysis of the data by displaying stabilities,

Measurements of ozone variation with height by balloon-borne or aircraft-borne instruments have disclosed that there is considerable ozone structure in the atmosphere. Variations in ozone structure are frequently found to coincide with variations in the temperature-humidity structure. By noting this coincidence and observing the movement and continuity of a specific structural detail, such as a temperature inversion which has a specific potential temperature, one can surmise the movement and horizontal extent of the accompanying layer of ozone.

Example Diagram--Figure 23 (a and b) presents two diagrams used to depict the variations of ozone, temperature and dew point with height. It shows ozone, temperature and dew point conditions which prevailed before the front passed. The bottom diagram presents a plot of the ozone sounding made during an airplane spiral near East Alton, Ill. on July 21 between 06:05 and 07:23 CDT (Appendix B, page B-40). The top diagram is a plot of the results of a balloon sounding of temperature-humidity made by the NOAA weather station at Salem, Illinois, for the 1200 GMT (Greenwich Meridian Time equivalent to 07:00 CDT) regularly scheduled sounding. Salem is 60 miles east of the Bethalto-East Alton area.

Figure 23 (a) is a portion of an Air Force Skew T, log p type adiabatic diagram. Isotherms in degrees Celsius slope upward from left to right. Three dry adiabats (lines of constant potential temperature) for 20, 30, and 40 C are shown as curved lines sloping from lower right to upper left. Water vapor mixing ratios (in grams of water vapor per kilogram of dry air) are the dashed lines sloping upward from lower left to upper right. Horizontal lines are isobars (lines of constant pres-



(a)

(b)

Figure 23. Temperature, dewpoint and ozone concentration variations with height in central Illinois on the morning of July 21, 1977, before the cold front passed. The (a) diagram is a plot of temperature in degrees C (solid line) and dewpoint (dashed line) for NOAA's Salem, Illinois station at 07:00 CDT. The (b) diagram is a plot of ozone mixing ratio (ppmm) measured over East Alton, Illinois between 06:05 and 07:23 CDT. See text for description of the (a) skew T, log p diagram and the (b) ozonagram.

sure). Atmospheric pressures are indicated on the left-hand ordinate with heights in thousands of feet on the right-hand ordinate. The pressure-height relationship on the diagram is that of the U.S. Standard Atmosphere, so for most soundings either the pressure or the height of a temperature feature will be slightly incorrect.

Figure 23b shows the results from Flight 6 converted to the form of an ozonagram(12) to portray the variations of ozone from the surface to the upper stratosphere. The diagram here has been designed so that the isobars and height lines are identical with those on the Skew T. log p diagram. The lines curving upward to the left are ozone mixing ratio lines. An ozonagram depicts mixing ratio as parts per million by mass (ppmm) rather than parts per million by volume (ppmv). The aircraft sounding measurements of ozone in parts per million by volume were multiplied by 1.65 to convert to parts per million by mass. Ozone mixing ratio is a conservative property of an air parcel and will not change during vertical movements unless turbulent mixing occurs.

The temperature lapse rate on the morning of July 21 was generally uniform and slightly stable up to 460 mb (20,000 feet) where there was a stable layer (temperature inversion). The layer from the surface to 400 mb (23,000 feet) was quite moist as shown by the dew point sounding (dashed line) which parallels the temperature plot. The relative humidity for the layer from the surface to 400 mb varied between 60 and 95 percent. Temperatures were also measured during the airplane sounding, but humidity was not; thus, the Salem sounding is plotted here so that both parameters can be shown.

Reiter(13) has stated that the ozone which appears in moist upper-air layers of the troposphere is of surface origin as compared with very dry layers which are indicative of stratospheric air. Thus the ozone which reached a concentration of 0.109 ppmm (.066 ppmv) at 3000 feet over East Alton was part of a deep layer of surface-generated ozone on the backside portion of the high pressure area which dominated the southeastern section of the United States. Ozone concentrations of 0.1 ppmm may have extended even higher than the 10,000-foot limit of the airplane sounding. No barrier is found in the temperature sounding until the stable layer at 16,000 feet.

Analysis Techniques--While no conspicuous ozone peak and stable layer combinations appeared on the July 21 sounding, made before passage of the cold front, there were numerous examples on the cross-country flight soundings made behind the front. Several techniques were used to investigate these ozone peaks and to explain their origin.

The initial step was to identify the magnitude of the ozone peak in relation to the ozone concentrations above and below it. An isolated maximum would suggest that ozone had been transported adiabatically into an area. Uniform ozone mixing ratios through a considerable depth, such as in Figure 23(b) would indicate that the ozone originated at the surface and was mixed upward.

Further investigation of this aspect involved comparison of the ozone sounding details with those of the temperature sounding. Ozone spikes appearing at the same height as temperature inversions were likely to have moved with this stable layer. They could be tagged with the potential temperature range of the stable layer and other soundings could be examined for evidence of this same stable layer. Occasionally, a part of the ozone peak might extend below or above the inversion layer. In these cases it was assumed that the lag time of one of the instruments was the cause for the misalignment and that the ozone peak actually coincided with the stable layer.

As previously mentioned, water vapor mixing ratio and potential vorticity value can distinguish air of stratospheric origin within the troposphere. Values of both these parameters were determined during the analyses of the soundings made during the cross-country flight. Data acquired during the aircraft sounding were insufficient for calculating potential vorticity so information gathered from NOAA soundings in the vicinity was used to plot the value of this parameter versus height. Vertical profiles of water vapor mixing ratios for the NOAA sounding closest in time and distance to the aircraft sounding were also prepared.

As identifiers of stratospheric air, Reiter and Mahlman(14) have recommended water vapor mixing ratio values less than 1.4 grams/kilogram and potential vorticity values greater than 10 x 10^{-9} cm sec deg

gm^{-1}. Potential vorticity is conserved during dry adiabatic descent and is thus an indication of stratospheric air which has entered the troposphere. In the present study there were several distinct potential vorticity maxima which had values less than 10×10^{-9} cm sec deg gm^{-1}. These smaller maxima probably indicate stratospheric air which has been partially mixed with tropospheric air.

Another technique used in this investigation of the high altitude ozone concentrations was to trace the air accompanying an ozone maximum backward in time along an isentropic surface. It was anticipated that this isentropic trajectory would show the path of adiabatic descent followed by stratospheric air from the tropopause to the point of the aircraft sounding. The choice of an isentropic surface was determined by the potential temperature of the subsidence inversion layer associated with the ozone maximum. The trajectory was constructed in 12-hour steps using the wind and pressure data from the NOAA sounding network. Movement along an isentropic trajectory assumes that no turbulent mixing occurs and that the route is dry. If there was a stable layer on a sounding in the vicinity of each 12-hour end point of the trajectory, its appearance was taken as confirmation of the continued adiabatic movement of the parcel.

Sounding Results From the Battelle Cross-Country Flights--

Springfield, Illinois--10:30 CDT, July 22--Shortly after the initial leg of the Battelle cross-country flight began, the first spiral sounding was made between 3,000 and 12,000 feet above a location near Springfield, Illinois (Appendix B, pages B-10, B-43). Results of this sounding are plotted in parts a and b of Figure 24. Plots of the variation with height of potential vorticity and water vapor mixing ratio are presented in Figure 24c. These are based on data collected during the regularly-scheduled NOAA rawinsonde sounding at Peoria, Illinois, made about 3-1/2 hours earlier (07:00 CDT). Peoria is 70 miles north of Springfield. NOAA records indicate that the cold front passed both Peoria and Springfield during the previous afternoon. On the morning of July 22 the frontal surface (appearing as an inversion layer) would have overlain both cities. As a consequence of the aircraft sounding being later than the NOAA sounding, it is expected that the frontal surface would appear at a higher elevation above Springfield.

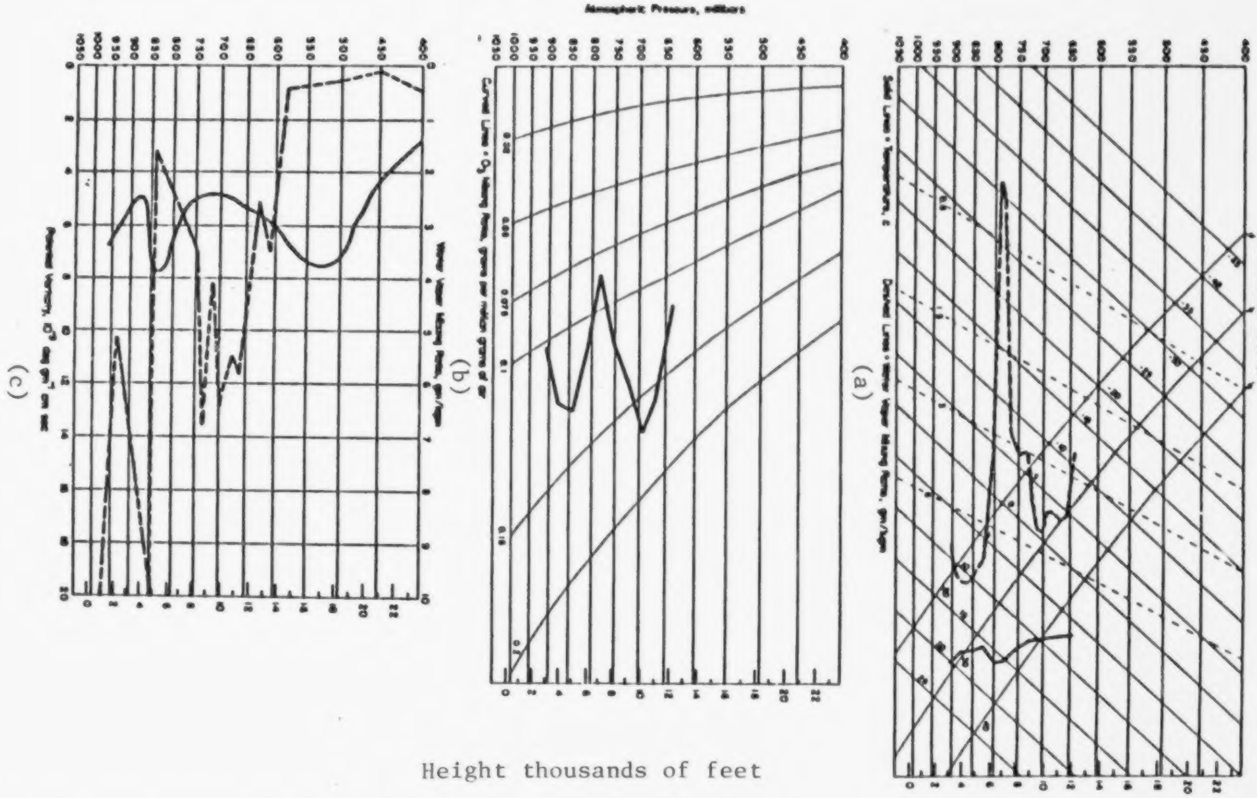


Figure 24. Information from central Illinois obtained from upper-air soundings made on the morning of Friday, July 22. (a) temperature (solid line) and dewpoint (dashed line) measured by Battelle aircraft at 10:30 CDT above Springfield, Illinois, (b) ozone mixing ratio (ppmm) measured by Battelle aircraft at 10:30 CDT, (c) Peoria, Illinois, potential vorticity (solid line) and water vapor mixing ratio (dashed line) measured by NOAA Rawinsonde network at 07:00 CDT.

Temperature measurements (solid line on the right of Figure 24a) depict a temperature inversion between 5,000 and 7,000 feet with a potential temperature range of 32 to 36C. The dewpoint (dashed line in Figure 24a) in this inversion layer decreased to a temperature where the water vapor mixing ratio was less than 0.6 gm/kgm at 6500 feet. The corresponding feature on the earlier Peoria sounding is water vapor mixing ratio of 17 gm/kgm at 5000 feet (dashed line on Figure 24c).

Variation of potential vorticity (P) with height is shown by the solid line in Figure 24c. A maximum of P (7.8×10^{-9} deg gm^{-1}cm sec) is located between 4,000 and 6,000 feet. It coincides with the dry layer there; thus one may conclude that the P maximum is associated with the frontal layer. The maximum value of P does not meet the Reiter criterion (10×10^{-9} deg gm^{-1}cm sec) for stratospheric air; however, the water vapor mixing ratios on the aircraft sounding indicate that the air is dry enough (less than 1.4 grams/kgm) to be of stratospheric origin. Our conclusion is that the portion of the stable layer observed above Peoria contains stratospheric air that has been diluted by tropospheric air.

Ozone measurements made during the aircraft sounding are plotted in Figure 24b. Two distinct maxima were observed, one between 4,000 and 5,000 feet and the other at 10,000 feet. However, there is a minimum at 7,000 feet which is the height of the dry inversion layer over Springfield. Thus the frontal zone contains little ozone and it can be assumed that no ozone was supplied to the surface at the time of the frontal passage. As noted previously, the ozone concentration at the Bethalto station dropped at the time of the frontal passage and continued to decrease.

Still to be explained are the ozone maxima at 4500 feet and 10,000 feet. Temperature structure, moisture content, and potential vorticity of the air at these levels all indicate that this air is not of recent stratospheric origin. However, the heights of these ozone maxima are high enough that there is some question as to whether they are of surface origin. To investigate the origin of these ozone maxima, isentropic trajectories were constructed tracing the air backwards from the Peoria-Springfield area. Isentropic trajectories show three dimensional motion. However, their construction requires adiabatic motion and an assumption of adiabatic movement may not be true in this instance.

The lower layer trajectory (potential temperature of 30C) is shown in Figure 25. The air parcel was carried backward for two days in four 12-hour steps. During this period the parcel was behind the front moving in a clockwise direction from southern Wisconsin to central Illinois. It ascended from 950 mb (about 2000 feet) to 845 mb (about 5000 feet). Apparently ozone generated at the surface was transported upward within the boundary layer and accumulated at the top of this layer. Destruction of the ozone in the lower portion of the layer left an ozone maximum (0.135 ppmm or about 80 ppbv) at the top of the layer. Potential urban sources for this ozone are the medium-sized cities of Des Moines, Iowa (population 194,000), Madison Wisconsin (173,000) and Rockford, Illinois (141,000). It is noteworthy that this ozone maximum of about 80 ppbv (130 ppbm) appeared at the top of the boundary layer above central Illinois less than one day after the frontal passage and without the air passing over a major city.

Figure 26 displays the isentropic trajectory for the upper ozone maxima ($\Theta = 39C$) carried backward 2-1/2 days. There was little vertical motion indicated during this time; the parcel remained at about 700 mb. This parcel was always in the high pressure area that existed over eastern United States preceding the arrival of the new front (refer to Figure 23 for the concentrations measured at 10,000 feet 24 hours earlier). At Springfield on July 22, this air with relatively high ozone still existed above the wedge of the new cold front. The trajectory indicates a meandering around the backside of the old high pressure area. As stated previously, the mixing ratios at 10,000 feet indicate that the air at this height had been mixed with surface air. Even if the ozone had been of stratospheric origin at one time, there is no way of identifying it as such by July 21 or 22.

Fond du Lac, Wisconsin--15:00 CDT, July 22--A second spiral sounding on the flight of July 22 was made in the afternoon over Fond du Lac, Wisconsin, 50 miles northeast of Milwaukee (see Appendix B, pages B-10, B-44). The cold front had passed over this area 2 days earlier on July 20. By the time of the sounding the front was two states away to

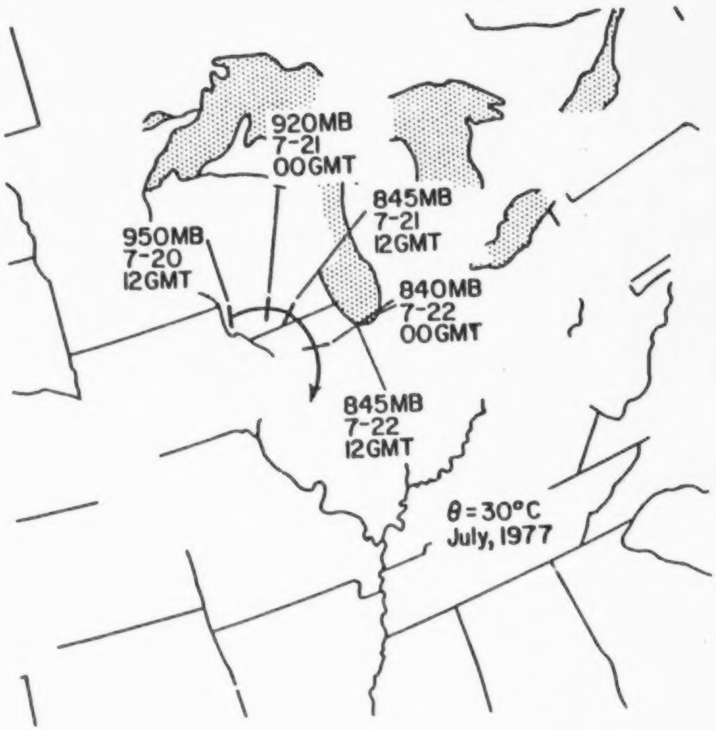


Figure 25. Isentropic trajectory traced backward in 12-hour steps on the Θ = 30 °C surface from Peoria, Illinois, at 1200 GMT (07:00 CDT) on July 22 to 1200 GMT on July 20.

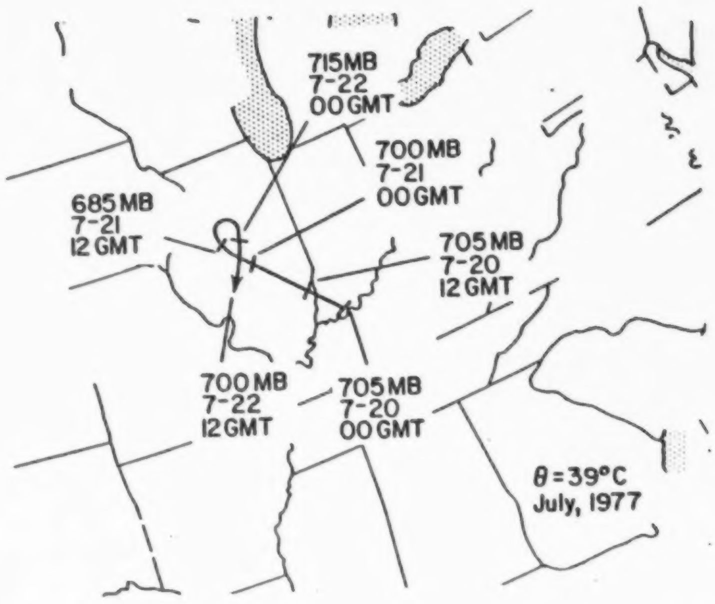


Figure 26. Isentropic trajectory traced backward in 12-hour steps on the $\theta = 39$ °C surface from Peoria, Illinois, 1200 GMT (07:00 CDT) on July 22 to 0000 GMT on July 20 (19:00 CDT on July 19).

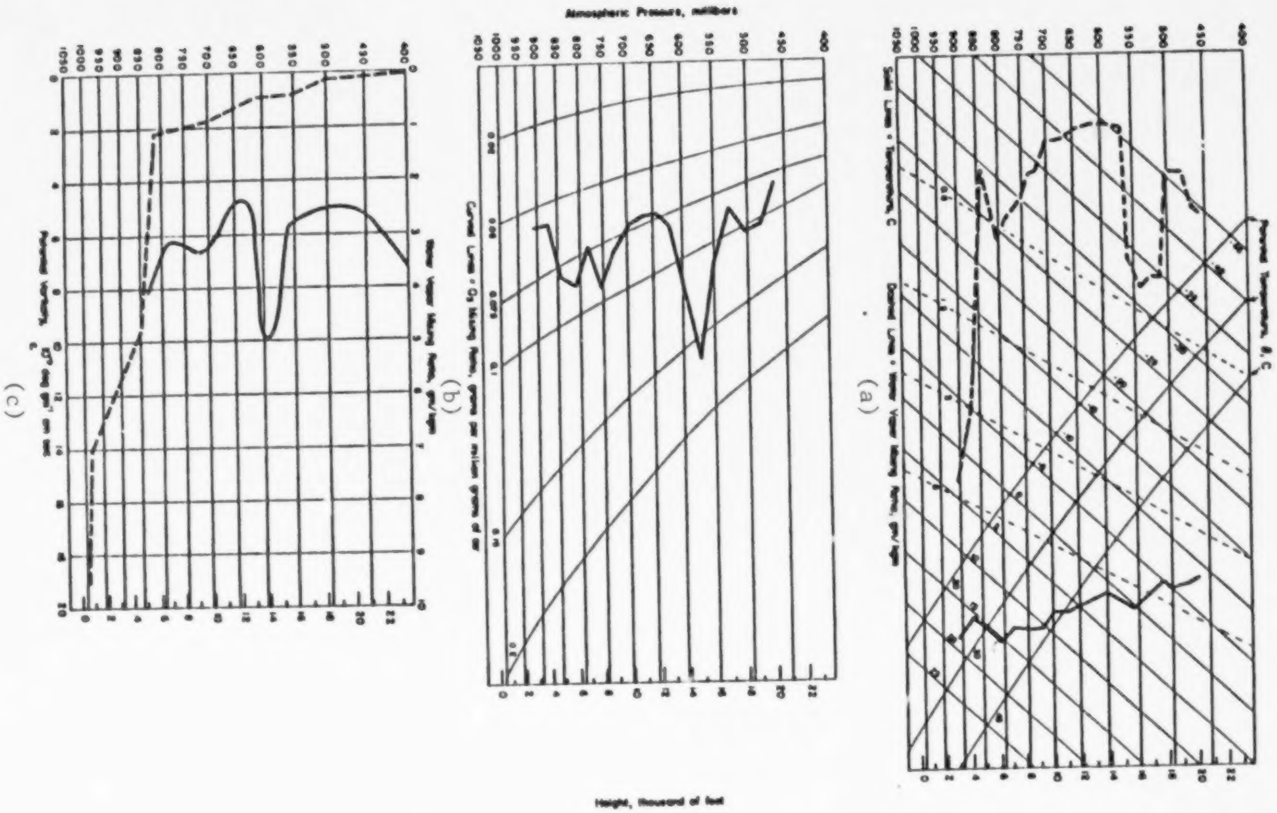
the south and southeast and the high pressure center was over Michigan. Surface winds over Wisconsin were from the southern quadrant.

Figures 27 a and 27b are plots of the aircraft sounding of temperature, dewpoint, and ozone while Figure 27c displays water vapor mixing ratio and potential vorticity as measured and calculated for the rawinsonde sounding at Green Bay, Wisconsin, 4 hours later and 50 miles north northeast of the Fond du Lac aircraft sounding.

An isothermal layer extends from 4000 feet to 6000 feet (Figure 27a) and has a potential temperature range from about 27 C to 34 C. It is the remains of the cold frontal layer that passed through on July 20. This layer coincides with a potential vorticity maximum at 5000 feet (Figure 27c) and has very low values of water vapor mixing ratio on both the Fond du Lac and Green Bay soundings. In contrast to the morning sounding at Springfield, the Fond du Lac sounding measured a relative maximum of ozone in the frontal layer (Figure 27b). The low water vapor mixing ratio and the relatively high potential vorticity of the layer suggest that this ozone had a stratospheric origin.

Examination of the water vapor mixing ratios throughout the depth of the two soundings reveals that the air from 5000 feet to 24,000 feet was dry enough to meet the criterion for stratospheric air. However, the plot of potential vorticity suggests that only the layer between 14,000 and 15,000 feet is actually the result of a stratospheric injection. The potential temperature meets the 10 x 10^{-9} deg gm^{-1} cm sec criterion for stratospheric air. There is a slightly stable layer at this height on the aircraft temperature sounding (Figure 27a). Furthermore, there is an ozone maximum of about 0.165 ppmm (0.100 ppmv) in the layer.

To investigate the origin of the ozone measured during this sounding, an isentropic trajectory was traced backward along the Θ = 44C surface from the Green Bay-Fond du Lac area at 14,000 feet (595 mb) on July 23 at 0000 GMT (19:00 CDT). Figure 28 depicts the 2-1/2 day trajectory of this ozone-rich parcel. At 1200 GMT (07:00 CDT) on July 20 the parcel was in the stratosphere at 300 mb (about 30,000 feet) above western Saskatchewan.



(a) (b) (c)

Figure 27. Information from central Wisconsin obtained from upper-air soundings made on the afternoon/evening of Friday, July 22, 1977, (a) temperature (solid line) and dewpoint (dashed line) measured by the Battelle aircraft at 15:00 CDT near Fond du Lac, Wisconsin; (b) ozone mixing ratio (ppmm measured by Battelle aircraft at 1500 CDT; (c) Green Bay, Wisconsin, potential vorticity (solid line) and water vapor mixing ratio (dashed line) measured by NOAA rawinsonde network at 1900 CDT.

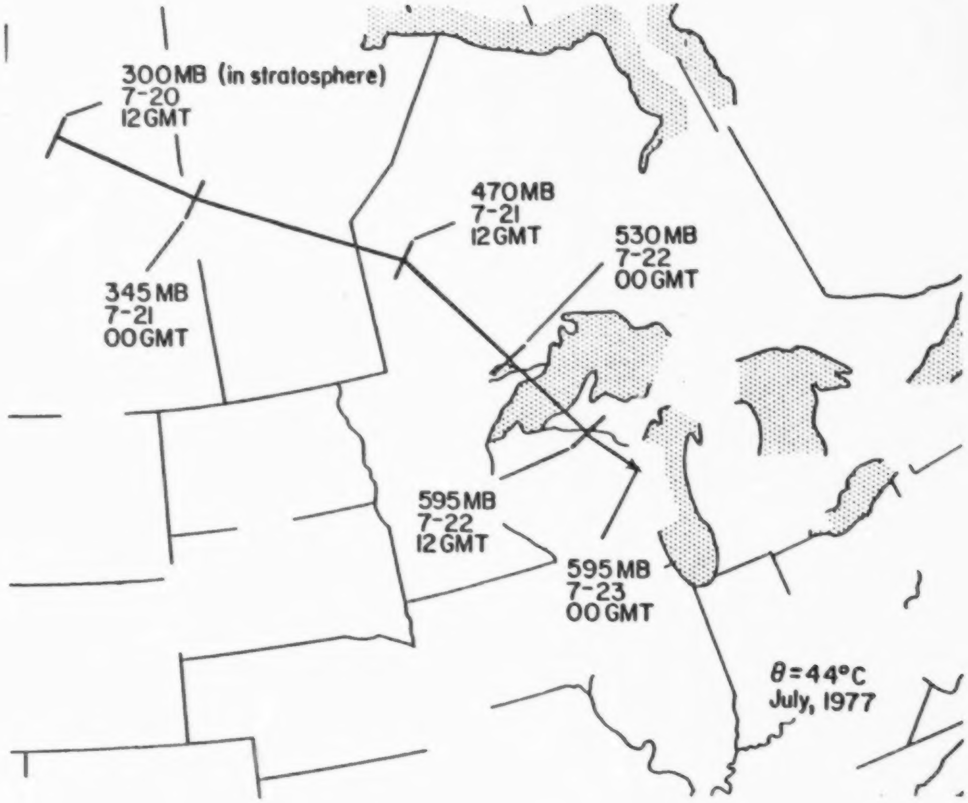


Figure 28. Isentropic trajectory traced backward in 12-hour steps on the $\Theta = 44$ °C surface from Green Bay, Wisconsin, at 0000 GMT on July 23 (19:00 CDT on July 22) to 1200 GMT (07:00 CDT) on July 20.

Figure 29 is a temperature-pressure plot of soundings made at three rawinsonde stations which were along the $\Theta = 44C$ air parcel trajectory during the 3 days. The Green Bay sounding (a) was made at 19:00 CDT on July 22. Twenty four hours earlier the closest sounding to the air parcel was the one at International Falls, Minnesota. When the parcel was at its minimum atmospheric pressure, 60 hours before it arrived over Fond du Lac, the nearest rawinsonde sounding was the one at The Pas, Manitoba.

Although the potential temperatures for the stable layer are not identical on the Fond du Lac, Green Bay, and International Falls soundings, they are close enough to confirm that they all represent the same air parcel. At The Pas the pressure of the $\Theta = 44C$ surface places it above the tropopause (the temperature inversion which begins at 325 mb).

Examination of the 500 mb map portions of Figures 17 and 18 indicates that the injection of the ozone-bearing stratospheric air along the $\Theta = 44C$ layer was associated with the low-pressure trough which moved across Canada. On July 20 at 1200 GMT (07:00 EST) the low center at 500 mb was at 60° north latitude and 90° west longitude. The trough at 500 mb at this time was oriented in a southwest direction from the low center. At 300 mb (about 10,000 feet higher up) this trough would have been displaced to the west. The stratospheric air injection over western Saskatchewan associated with this 300 mb trough resulted in a stable layer in the middle troposphere. This layer was not a frontal layer and did not extend to the surface. Thus the ozone within it would not be transported directly to low elevations, but would remain in the middle troposphere until dissipated by mixing which occurred there.

The three temperature soundings in Figure 29 also indicate the presence of a stable layer at lower elevations. This stable layer has a potential temperature in the vicinity of 30C and thus corresponds to the frontal layer observed on the Springfield and Fond du Lac aircraft soundings. The temperature inversions denoting this stable layer on Figure 29 are at 5000 feet above Green Bay, 6000 feet above International Falls, and 10,000 feet above The Pas. The layer would have to rise to considerably higher elevations to reach the stratosphere. Thus, the tropopause injection point of the ozone found in this layer at Fond du Lac must have been further west than western Saskatchewan, the injection point for the air on the $\Theta = 44C$ surface.

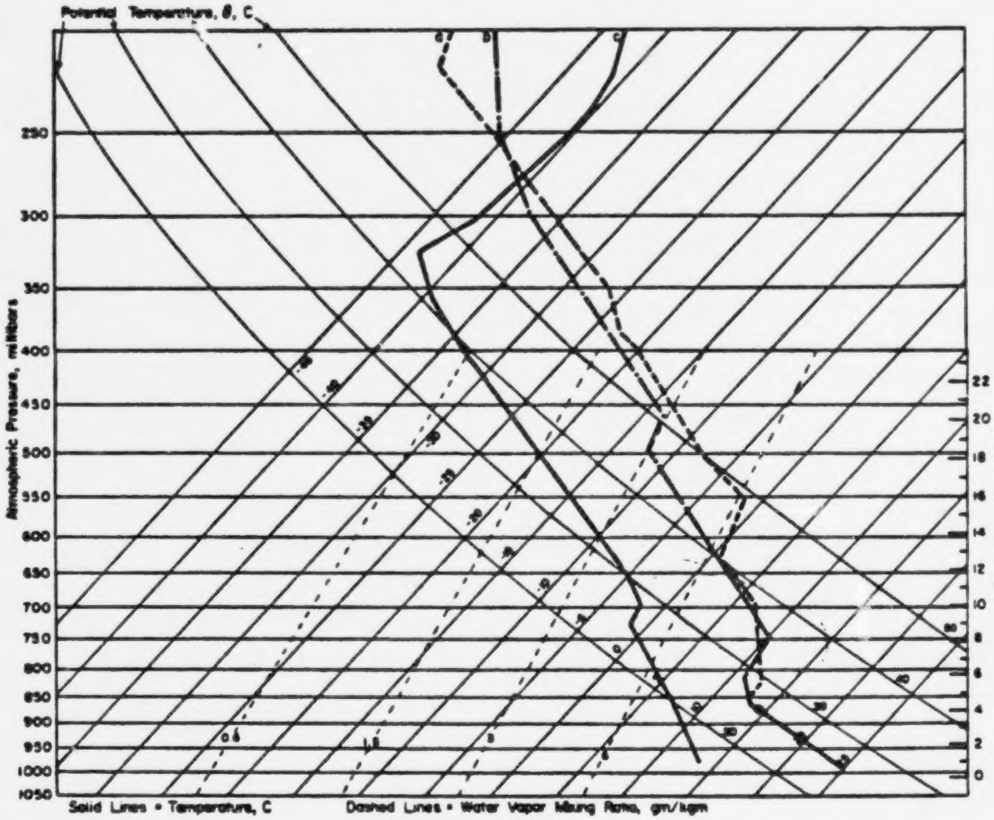


Figure 29. Three temperature soundings made along the Θ = 44°C isentropic trajectory of Figure 28 showing the descent of the stable layer from the stratosphere to the middle troposphere. Green Bay, Wisconsin, at 0000 GMT on July 23 (dashed line). International Falls, Minnesota, at 0000 GMT on July 22 (dash-dot line). The Pas, Manitoba, at 1200 GMT on July 20 (solid line).

Muskegon, Michigan--15:00 CDT, July 23--The second leg of the cross country flight was made from Muskegon, Michigan, eastward to Buffalo, New York, and then southwestward to Columbus, Ohio, covering the period from 14:00 EDT to 20:40 EDT on Saturday, July 23. The first spiral sounding on this flight was made about 50 miles east of Muskegon. At the surface this location was well back of the high pressure center and winds were from the south or southwest (refer to Figures 21 and 22). At 500 mb the low pressure trough was also east of Michigan and the upper level winds over the state were west northwest.

Results of the airplane soundings are displayed in Figures 30a and 30b while Figure 30c is a plot of the potential vorticity and mixing ratio from the Flint, Michigan, rawinsonde sounding made at 20:00 EDT on July 23, 5 hours later than the aircraft sounding. Flint is about 80 miles east of the point where the aircraft sounding was made.

During the aircraft sounding which covered the layer between 2000 feet and 12,000 feet, several ozone peaks were measured. The highest ozone was found just below the upper extent of the sounding. A smaller peak was found between 5000 and 6000 feet while between 5000 feet and 2000 feet the ozone never dropped below 0.125 ppmm (0.075 ppmv).

Both the aircraft sounding and the rawinsonde sounding reported very low water vapor mixing ratios between 6000 and 12,000 feet (dashed lines in Figures 30a and c). The potential vorticity curve (solid line in Figure 30c) leads one to conclude that within this dry air there were two layers of air which still had traces of their stratospheric origin. One of these is at about 10,000 to 12,000 feet while the other lies between 5000 and 6000 feet.

The potential vorticity plot from the Flint sounding (solid line on Figure 30c) contains a maximum of nearly 10×10^{-9} deg gm^{-1} cm sec at about 10,500 feet. It is hypothesized that this layer is associated with the temperature inversion and ozone maximum which appeared at about 11,500 feet (Figures 30a and c) on the aircraft sounding. The potential temperature of this inversion layer on the aircraft sounding was 42C. Thus this is apparently part of the same injection (Θ = 44C) that was traced back to the stratosphere in Figure 28.

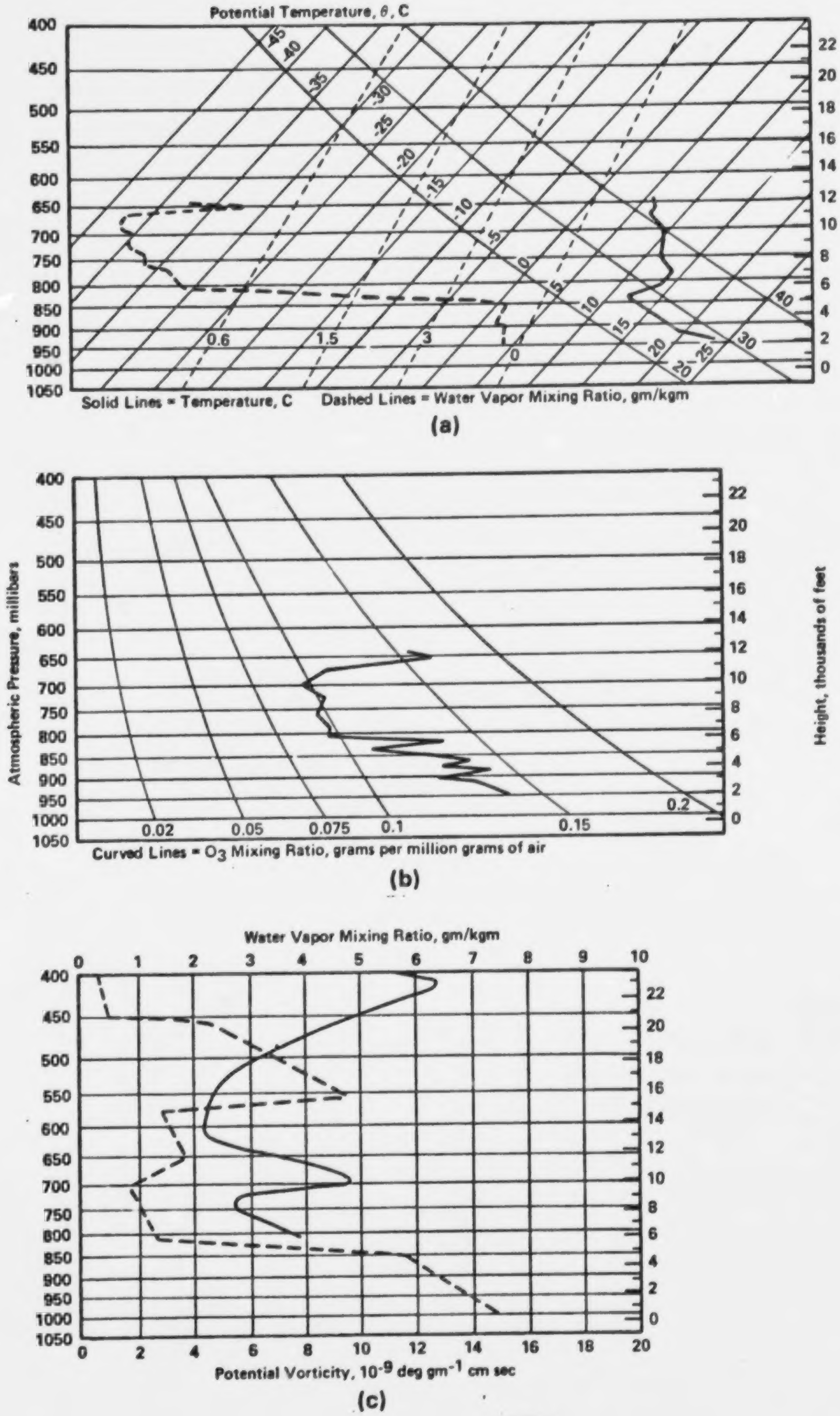


Figure 30. Information from central Michigan obtained from upper air soundings made on the afternoon/evening of Saturday, July 23, 1977. (a) Temperature (solid line) and dewpoint (dashed line) measured by Battelle aircraft at 15:00 EDT east of Muskegon, Michigan; (b) ozone mixing ratio (ppmm) measured by Battelle aircraft at 15:00 EDT; (c) Flint, Michigan, potential vorticity and water vapor mixing ratio measured by the NOAA rawinsonde network at 20:00 EDT.

Between 5000 and 6000 feet there is a potential vorticity maximum and a marked temperature inversion with a potential temperature of 30C, but no distinct ozone maximum. This is the layer that was identified as the frontal layer observed on the two aircraft soundings of the previous day. Ozone content on this central Michigan sounding is uniform at 0.10 ppmm (0.06 ppmv) between 6000 and 10,000 feet. This concentration is similar to the concentrations associated with the frontal layer on the earlier soundings.

At about 22,000 feet (425 mb) on the Flint sounding (Figure 30c) there are indications of a layer of air which has stronger stratospheric characteristics than any of the previously noted injections. The high elevation, the low mixing ratio (0.5 gm/kgm) and the high potential vorticity (12.5×10^{-9} deg gm^{-1} cm sec) all suggest air that was recently in the stratosphere. Unfortunately, the aircraft sounding was not high enough to measure the ozone in this layer.

Between 2000 and 5000 feet the ozone concentration varies between 0.10 and 0.145 ppmm (0.06 to 0.09 ppmv). The temperature lapse rate and the relatively high moisture content in this layer lead to the assessment that this is ozone generated at the surface. It has been mixed upward until stopped by the barrier of the temperature inversion at 5000 feet.

Erie, Pennsylvania--19:00 EDT, July 23--A spiral sounding was made midway between Buffalo, New York, and Erie, Pennsylvania, late in the second leg of the cross country flight (see Appendix B, pages B-10, B-46). This sounding explored the layer between 2000 and 20,000 feet. Results of the aircraft sounding are shown in Figures 31a and 31b. This sounding was made within 50 miles of the Buffalo rawinsonde station and within one hour of the regular Buffalo 0000 GMT (20:00 EDT) sounding. Water vapor mixing ratio and potential vorticity for Buffalo are displayed in Figure 31c. Comparison of the observations from the two soundings provided an estimate of the accuracy range for the instruments and data reduction methods used. For instance, the water vapor mixing ratios on the aircraft sounding were lower than those on the balloon; but the aircraft sounding picked up mixing ratio variations between 9000 and 13,000 feet that the rawinsonde did not record.

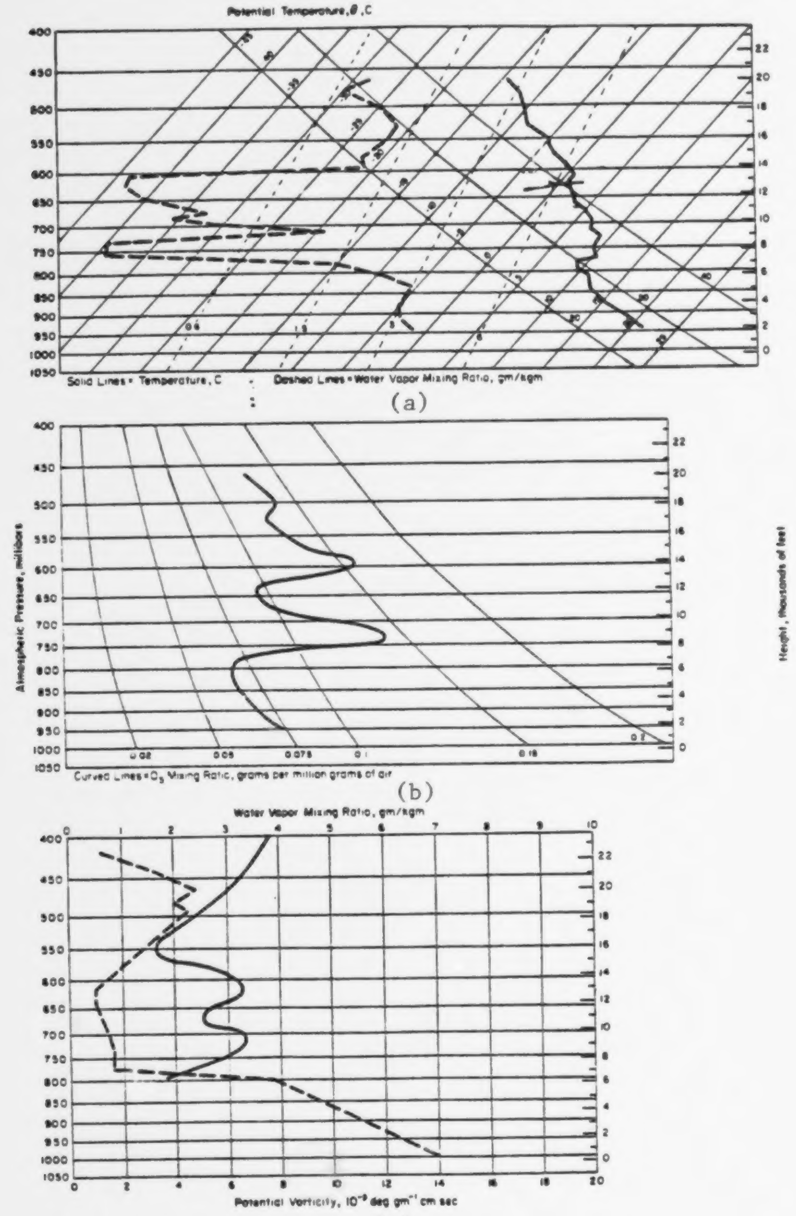


Figure 31. Information from western New York obtained from upper-air soundings made on the evening of Saturday, July 23, 1977. (a) Temperature (solid line) and dewpoint (dashed line) measured by Battelle aircraft at 19:00 EDT northeast of Erie, Pennsylvania, (b) ozone mixing ratio (ppmm) measured by Battelle aircraft at 19:00 EDT, (c) Buffalo, New York potential vorticity and water vapor mixing ratio measured by the NOAA rawinsonde network at 20:00 EDT

Examination of Figure 31 shows that two stable temperature layers are present as they were on previous soundings. The dry layer with a potential temperature of 42C is located at a height of about 13,000 feet while the dry layer with a potential temperature of 31C is at 7000 feet. There are dual maxima of potential vorticity (Figure 31c) as appeared in the mid troposphere on earlier soundings, but their values are lower than previously observed. Moreover, while the upper potential vorticity maximum coincides with the dry inversion layer, the lower potential vorticity maximum is associated with a stable layer slightly above the Θ = 30 C surface. The Θ = 30 C surface actually coincides with a potential vorticity minimum.

There is another stable layer (Θ = 35 C) at a height of about 9000 feet. It contains an ozone maximum of 0.14 ppmm, which is about twice as large as the ozone maximum contained in the frontal layer (Θ = 31 C) on earlier soundings. The ozone maximum within the Θ = 42 C layer is about the same (0.155 ppmm) as on earlier soundings.

Earlier, Figure 25 presented the backwards isentropic trajectory of an air parcel which was found just below the frontal surface above Peoria, Illinois. This trajectory was performed on the Θ = 30C surface. It was found on later soundings that frequently the potential temperature of 30C was within the frontal layer instead of beneath it as was true on the Peoria sounding.

Another backwards isentropic trajectory was constructed on the Θ = 30C surface beginning at a point north of Buffalo at the time of the Erie aircraft sounding. For this trajectory the Θ = 30C surface represented the path that an air parcel would take along the cold front layer. Figure 32 displays the path of this trajectory. The backwards trajectory from Green Bay along the Θ = 44C surface (Figure 28) is also shown to point out similarities between the paths of the two trajectories. Both parcels descended; however, the upper air parcel (Θ = 44C) descended more rapidly. It went from within the stratosphere at 300 mb to 595 mb, a height differential of about 15,000 feet in 60 hours. During the same time period (1200 GMT on July 21 to 0000 GMT on July 23) the parcel on the Θ = 30C surface descended from 630 mb to 780 mb, a height differential of about 5000 feet.

An attempt was made to trace the parcel on the Θ = 30C surface back to a point where the parcel was within the stratosphere. This goal was not achieved. For about 2-1/2 days prior to July 20 the pressure level remained constant and no descent was shown in the trajectory. However, as is shown in Figure 32, there were rawinsonde stations in British Columbia July 17 and 18 at which the Θ = 30C surface was in the stratosphere. It is concluded that the frontal layer air and the relatively high ozone concentrations did actually originate in the stratosphere; however, the isentropic trajectory method used in this analysis was not refined enough to precisely trace the parcel backward for the 4-5 day period needed to get from the tropopause to the lower troposphere.

An examination of the 500 mb chart for 07:00 EST (1200 GMT) shown in Figure 16 shows that the low-pressure trough was above British Columbia at the time of the presumed injection of stratospheric air onto the Θ = 30C surface. This injection along the frontal surface supplied stratospheric air to the lower troposphere. Injections associated with this same trough (e.g., along the Θ = 44C surface) occurred at the later times and at locations further to the east (c.f. Figure 32). These later injections did not descend as deeply into the troposphere, at least while they were contiguous within the encompassing stable layer.

Toledo, Ohio--10:00 EDT, July 24--On Sunday, July 24, during the early part of the third leg of the cross-country flight, the Battelle aircraft made a sounding about 25 miles south of Toledo, Ohio. It was 3 days since the cold front had passed through this area and the region had been at the rear of the high pressure system for 2 days. Surface winds in the area were light and predominantly southerly or southwesterly (refer to Figure 22). Flow at 500 mb was primarily westerly. Above Toledo there were no longer any vestiges of the trough at 500 mb.

Figure 33 presents plots of the temperature, dew point, and ozone measurements made during this aircraft sounding (see Appendix B, pages B-10, B-47). In the lower part of the sounding, the 3000 to 5000 foot layer is neutrally stable (i.e., its temperature lapse rate follows

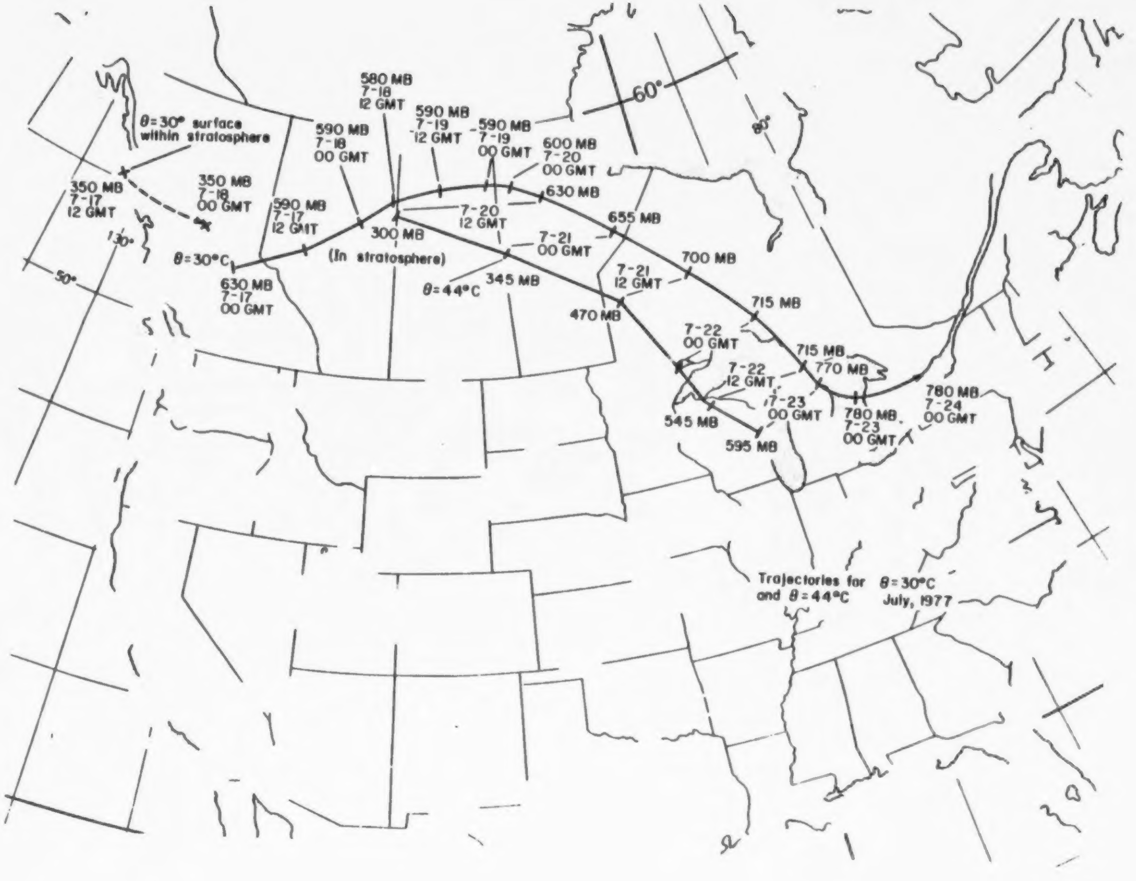


Figure 32. Isentropic trajectories traced in 12-hour steps on the Θ = 30°C surface from Toronto, Ontario, at 0000 GMT on July 24 (20:00 EDT on July 23) to Prince George, British Columbia, at 0000 GMT on July 17 (20:00 EDT on July 16). Pressures at each 12-hour step are given in millibars. The Θ = 44°C trajectory from Figure 28 is also shown.

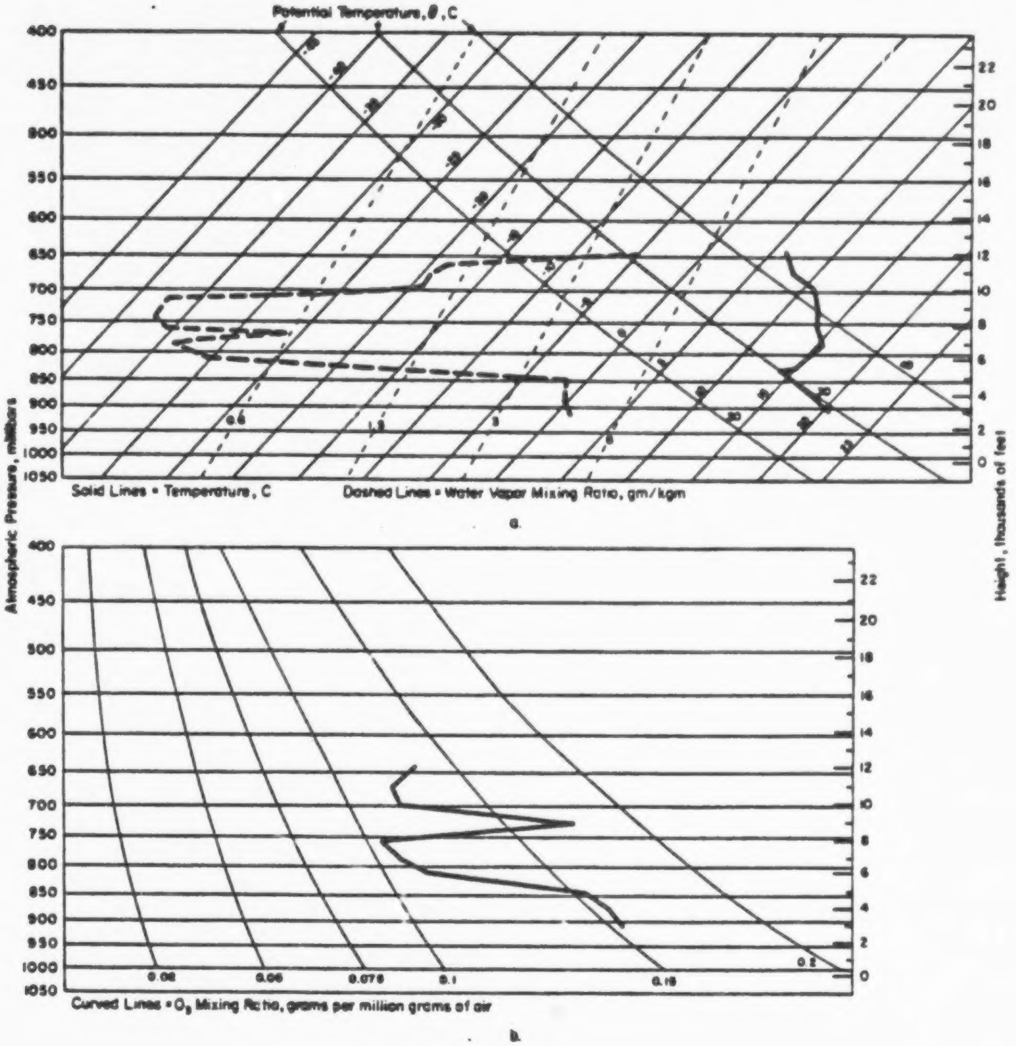


Figure 33. Measurements made during the Battelle aircraft sounding south of Toledo, Ohio on July 24, 1977 at 10:00 EDT, (a) temperature (solid line) and dewpoint (dashed line); (b) ozone mixing ratio (ppmm).

the adiabatic temperature line). Between 5000 and 10,000 feet the air is quite dry; however, the layer has two different temperature lapse rates. Between 5000 and 7000 feet the lapse rate is isothermal, while from 7000 to 10,000 feet the layer is slightly stable.

Ozone concentrations in the lower part of the dry layer between 5000 and 10,000 feet are uniform at 0.11 ppmm (0.067 ppmv); however in the less stable upper portion of the dry layer there is an ozone maximum of 0.175 ppmm (0.106 ppmv). The potential temperature associated with this ozone maximum is 40C which places it about midway between the potential temperatures of the two ozone maxima observed the previous evening over western New York (Figure 31). It is not clear whether the ozone maximum of 0.175 ppmm at 9000 feet above Toledo is part of either of the two ozone maxima above Erie or whether it represents still another stratospheric-air injection. The slightly stable lapse rate of the layer in which it is contained is similar to the lapse rate of the lower ozone layer at Erie but its ozone concentration is more nearly like the concentration of the upper ozone maximum at Erie.

Concentrations in the lowest layer (below the subsidence inversion base at 5000 feet) are higher than for any other sounding during this series. The uniformity of the ozone mixing ratio values (in ppmm or ppmv) with no gradient from lower to higher altitudes demonstrates that the tropospheric ozone (relatively high water vapor mixing ratio) in this layer has been uniformly mixed up to the base of the subsidence inversion at 5000 feet. This well-mixed layer with its relatively high ozone concentrations (0.155 ppmm or 0.095 ppmv) is indicative of aged air with ozone that was generated at the surface. The photochemical processes acting upon the precursor emissions from the states south of the Great Lakes has produced a massive ozone layer beneath the subsidence inversion. It can be expected to move across the eastern portion of the United States as the next cold front pushes the large high pressure area eastward. The high ozone concentrations within this layer have the potential to be mixed downward toward the surface on any afternoon when the temperature lapse rate is neutrally stable or unstable through the layer. If there is an ozone gradient from the upper portion of this layer to the surface, this mixing will add to the surface ozone concentrations.

Robinson, Illinois--10:00 CDT, July 23--As noted earlier, Washington State University, in their part of the study, also made a cross-country flight during this period to investigate the nitrogen oxides and oxidants within the high pressure area. One of their aircraft soundings was made above Robinson, Illinois, on Saturday morning July 23, at 10:00 CDT. Robinson is near the Illinois-Indiana border 75 miles north of Evansville, Indiana, and 150 miles east of St. Louis. A map showing the location of Robinson relative to the Battelle cross-country flight path is given in Figure 34.

At the time of the sounding, Robinson was in the southwestern portion of the large high pressure system with surface winds from the east. Six hours later, when the Battelle airplane made its sounding above Grand Rapids, Michigan, the winds in central Michigan were from the southwest and had traversed the Chicago area. Both sounding sites were in the northwest flow (see the 500 mb map in Figure 21).

Two temperature soundings and an ozone sounding are displayed in Figure 35. Figure 35a is the temperature sounding from the Washington State flight while Figure 35c is the temperature-humidity sounding made by NOAA at Salem, Illinois (75 miles southwest of Robinson) at 07:00 CDT that same morning. Within the dry layer of the atmosphere located above 5000 feet both soundings measured several stable layers. Only one layer of high ozone was within the dry layer -- a maximum of about 0.21 ppmm (0.13 ppmv) at 14,000 feet. The potential temperature associated with this maximum (Θ = 51C) is larger than any that were encountered on the other soundings. This suggests that this ozone entered the troposphere as part of another stratospheric injection during the movement of the low-pressure trough across Canada.

Mixing from the surface upward is limited by the base of the subsidence inversion (Θ = 32 C) which is the trailing portion of the frontal layer. The base of the inversion is located at a height of about 5000 feet which is nearly identical to its height above Springfield 24 hours earlier (Figure 24). It was concluded in the discussion of the Springfield sounding that the ozone maximum (0.13 ppmm) below the subsidence inversion had resulted

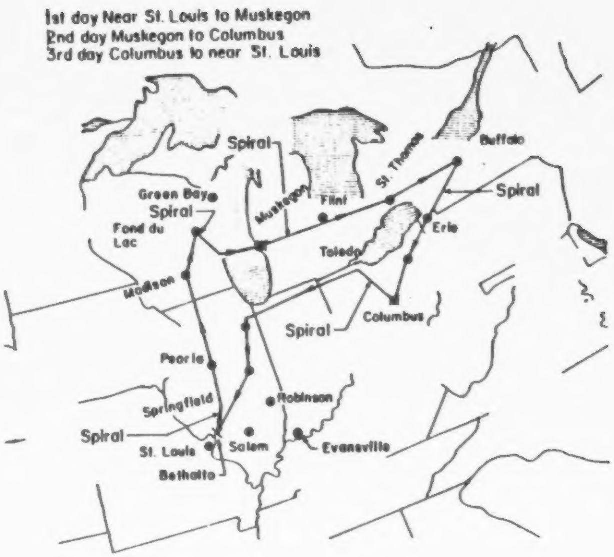
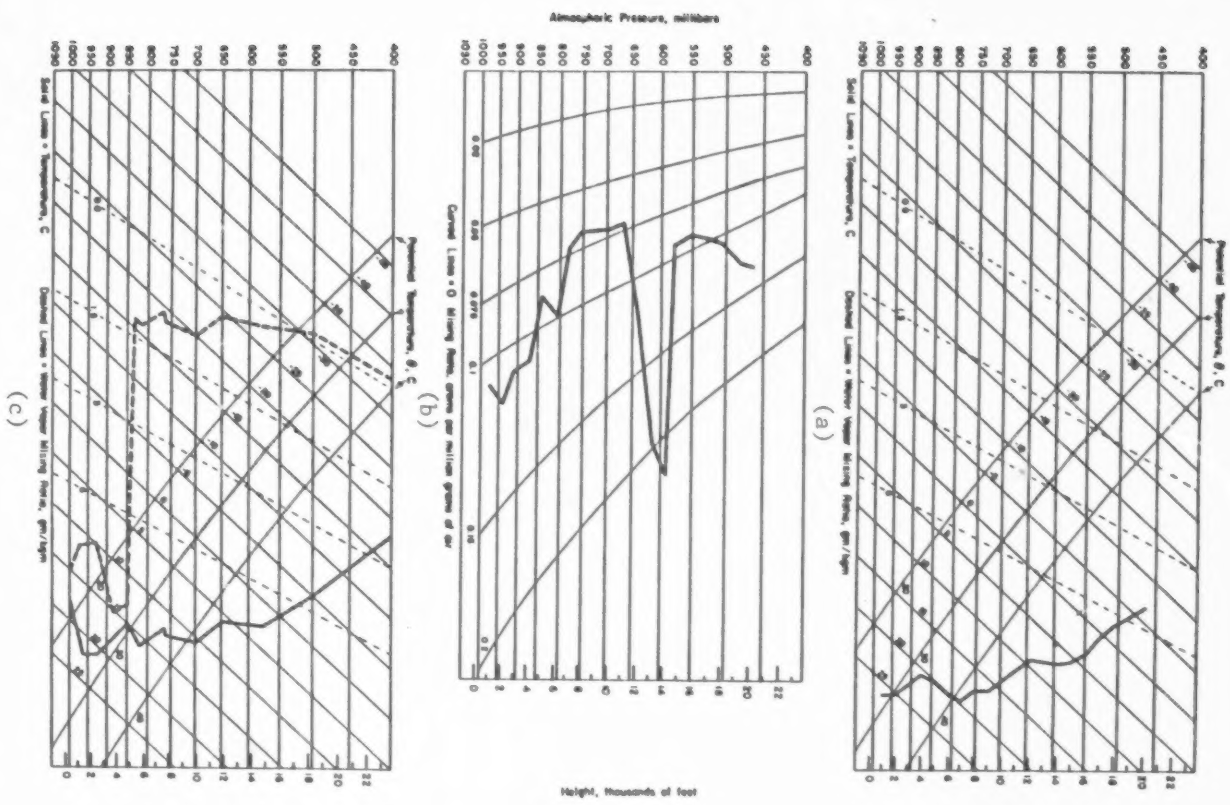


Figure 34. Path of Battelle cross-country flight showing location of spiral soundings, NOAA rawinsonde stations, and the Washington State University monitoring site at Robinson, Illinois.



(a)

(b)

(c)

Figure 35. Information from southeastern Illinois obtained from upper-air soundings made on the morning of Saturday, July 23, 1977, (a) temperature measured by Washington State University aircraft at 10:00 CDT above Robinson, Illinois, (b) ozone mixing ratio (ppmm) measured by Washington State aircraft at 10:00 CDT, (c) temperature (solid line) and dewpoint (dashed line) measured during NOAA rawinsonde sounding at Salem, Illinois, at 07:00 CDT.

from transport from a level near the surface. The ozone concentration at 5000 feet on the Springfield sounding was greater than the ozone concentrations below it, a situation which implies that there was no mixing upward from the surface to 5000 feet.

On the Robinson sounding of 10:00 CDT on July 23, there is a gradient of ozone concentrations from high levels at 4000 feet to lower levels at 5000 feet. There is a nearly adiabatic lapse rate between these heights which would also support the mixing hypothesis. Below 2000 feet the ozone decrease is probably related to nocturnal surface-based destruction processes.

Horizontal Extent of the Ozone Layers--

The aircraft spiral sounding measures the ozone concentrations above a single location at a single time. The question arises as to the extent of the ozone layer that is sensed during the sounding. One can hypothesize that the horizontal extent of a stratospheric injection of ozone into the troposphere can be estimated by using a single ozone sounding in combination with the routine temperature-humidity soundings made by the National Weather Service (NWS). The ozone sounding identifies one or more dry stable layers which contain ozone of stratospheric origin. An average potential temperature for each layer can be determined from this sounding. Using this information one can analyze the NWS soundings from surrounding stations and pick out those which have dry stable layers with similar potential temperatures.

This concept of a contiguous layer of stratospheric ozone moving within the troposphere has been studied using the aircraft spiral sounding data.

Several days of rawinsonde soundings made in the United States and Canada during the period of the cross-country flight were examined. Dry stable layers were sought in three potential temperature ranges (a) Θ = 25-30C, (b) Θ = 35-40C, and (c) Θ = 40-45C. The results of this investigation for the 1200 GMT (08:00 EDT) soundings on July 20, 22, and 23 are shown in Figures 36-44. These figures present a median atmospheric pressure for each of the three potential temperature categories and identify whether (1) a dry stable layer, (2) a wet stable layer, or (3) an unstable layer was recorded at this pressure. A wet stable layer is one which did not meet the 1.5 gm/kgm criterion for dryness. These data are displayed on a map which pictures the surface positions of the fronts and the high pressure center at 1200 GMT on the date in question.

Figures 36-38 exhibit the pressure, stability, and dryness of the layer which had potential temperatures (Θ) in the range 25-30C on the 3 days. The horizontal area designated as the dry stable layer is hypothesized to contain the stratospheric ozone. This dry layer included only the central portion of the entire stable layer. It generally lagged behind the position of the surface front by about 200 miles and did not descend below a pressure of 850 millibars. Between July 20 and 23, the dry area moved in a southeasterly direction, descended (as shown by the increasing pressures) and contracted in horizontal extent.

Examination of the three maps that depict the position of the dry stable layer which has potential temperatures in the range 35-40C (Figures 39-41) shows both similarities and differences between this stable layer and the previous one. It moves in a southeasterly direction, but it increases in size and there is no obvious tendency to descend. However, 12 hours later at 0000 GMT on July 24 (map not shown) this stable area did continue its movement to the southeast with descent. The size had decreased -- the dry layer covered only Ohio, Pennsylvania, West Virginia and New York.

These characteristics of the dry stable layer were also evident in the behavior of the Θ = 40-45C layer (Figures 42-44). It moved to the southeast following the front, and it descended toward high pressures. On the 23rd the layer had split in two. Twelve hours later (not illustrated) the layer was still in two parts but they had diminished in size.

Two airplane soundings through these layers were made by the Battelle aircraft on both July 22 and July 23. Positions of the soundings (Figures 24, 27, 30, 31) are denoted on the maps (Figures 37, 38, 40, 41, 43, 44). The aircraft soundings were made several hours after the NWS sounding times, consequently the dry stable layers are expected to be displaced southeastward of their illustration position by the time of the aircraft spirals.

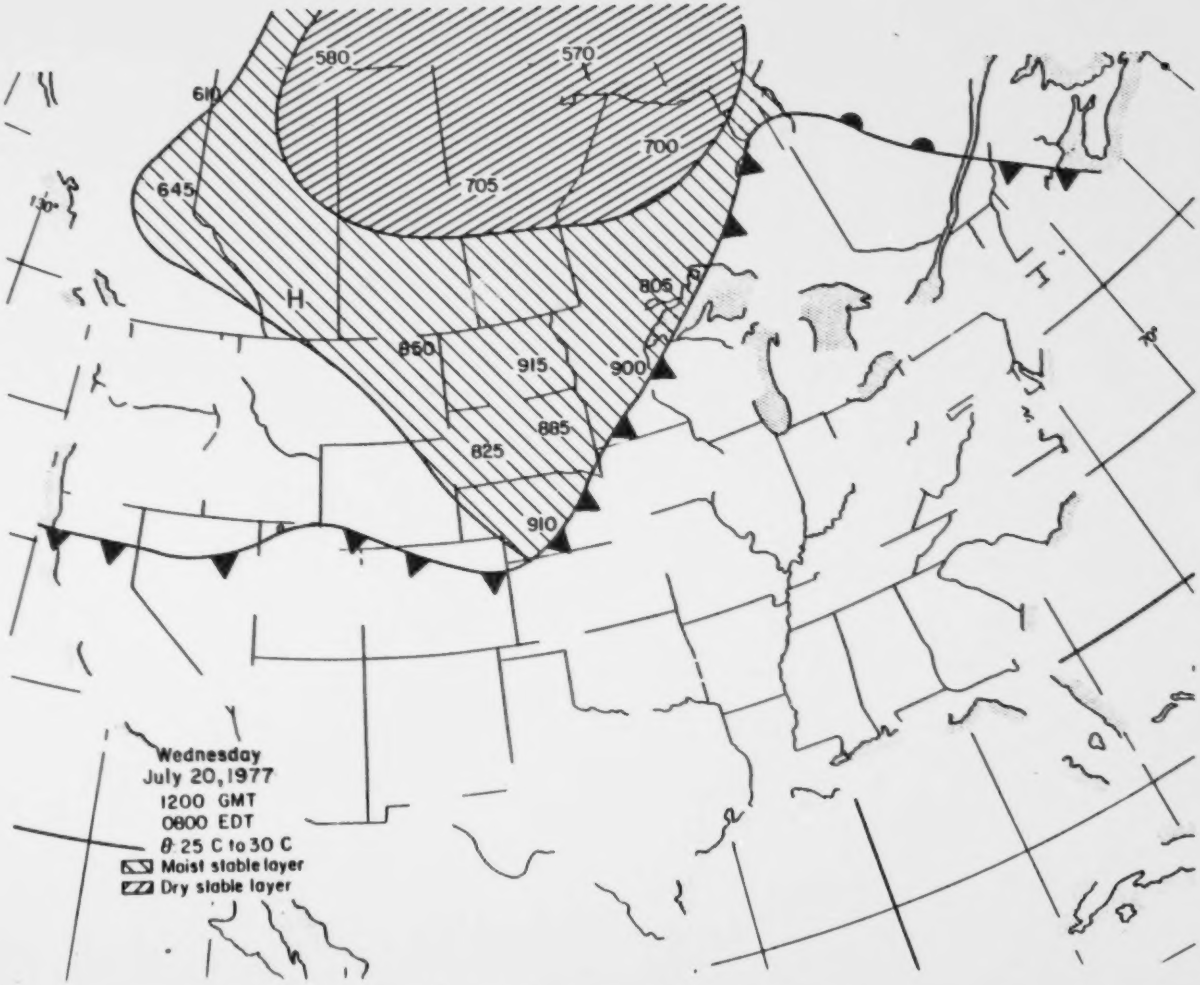


Figure 36. Horizontal extent of moist and dry portions of the stable layer with potential temperature between Θ = 25 °C and Θ = 30 °C on Wednesday, July 20, 1977 at 1200 GMT. Dry portions (water vapor mixing ratio <1.5 gm/kgm) are indicative of air with a stratospheric origin. Surface positions of front and high pressure center (H) are shown. Median pressure of the potential temperature surface at the rawinsonde stations is given in millibars.

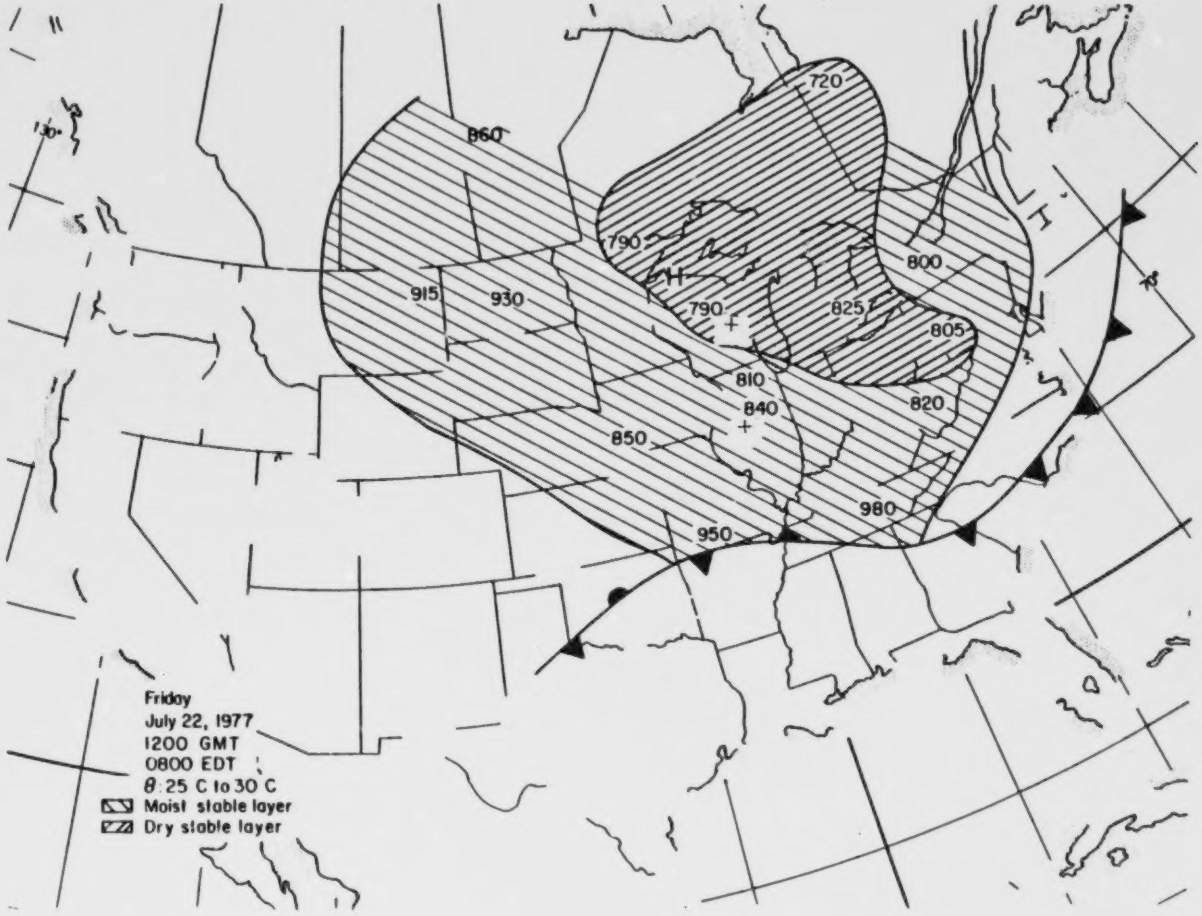


Figure 37. Horizontal extent of moist and dry portions of the stable layer with potential temperatures between $\Theta = 25$ °C and $\Theta = 30$ °C on Friday, July 22, 1977 at 1200 GMT. Dry portions (water vapor mixing ratio <1.5 gm/kgm) are indicative of air with a stratospheric origin. Surface positions of front and high pressure center (H) are shown. Median pressures of the potential temperature surface at the rawinsonde stations is given in millibars.

+ denotes the locations of the two aircraft soundings taken later this day.

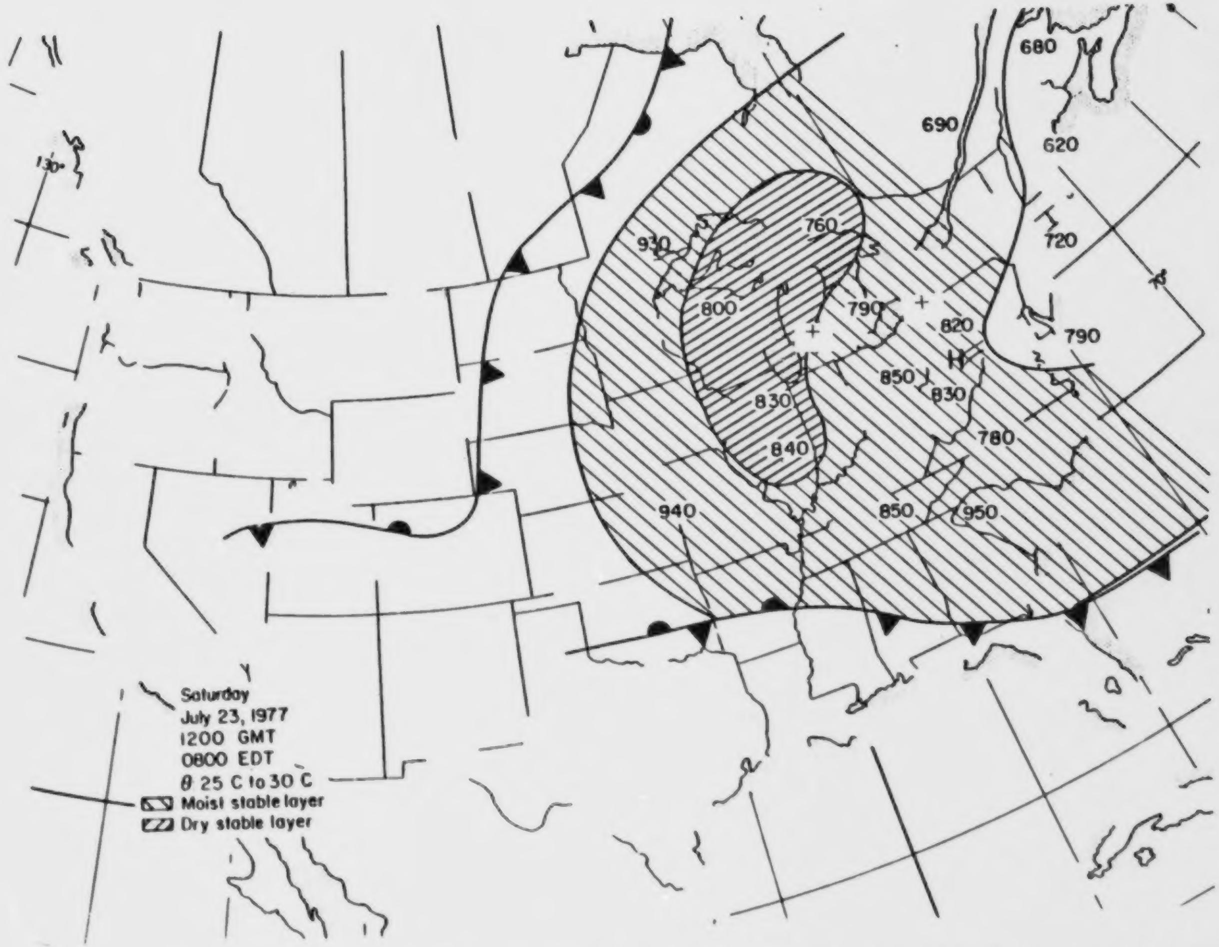


Figure 38. Horizontal extent of moist and dry portions of the stable layer with potential temperatures between Θ = 25 °C and Θ = 30 °C on Saturday, July 23, 1977 at 1200 GMT. Dry portions (water vapor mixing ratio <1.5 gm/kgm) are indicative of air with a stratospheric origin. Surface positions of fronts and high pressure center (H) are shown. Median pressure of the potential temperature surface at the rawinsonde stations is given in millibars.

+ denotes the location of the two aircraft soundings taken later this day.

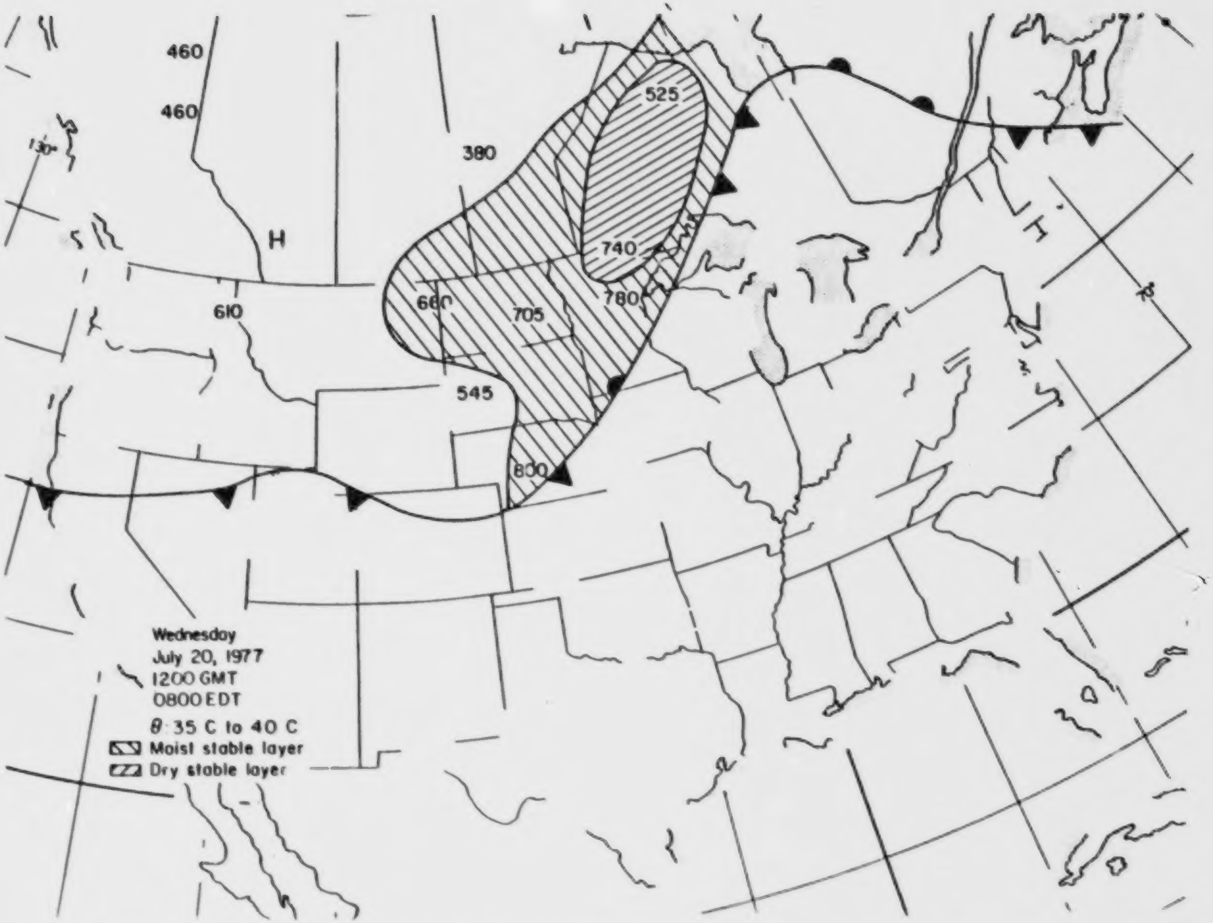


Figure 39. Horizontal extent of moist and dry portions of the stable layer with potential temperatures between Θ = 35 °C and Θ = 40 °C on Wednesday, July 20, 1977 at 1200 GMT. Surface positions of front and high pressure center (H) are shown. Median pressure of the potential temperature surface at the rawinsonde stations is given in millibars.

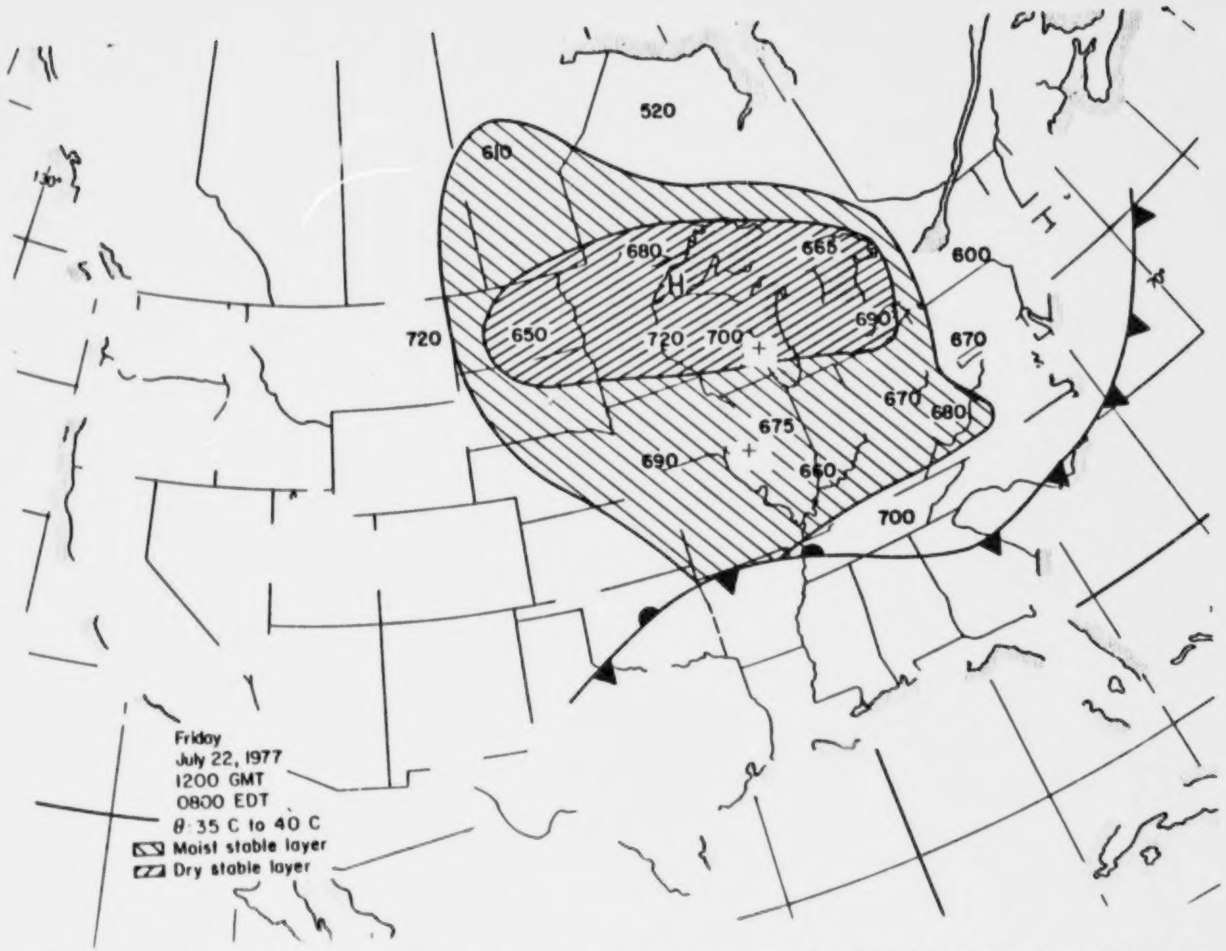


Figure 40. Horizontal extent of moist and dry portions of the stable layer with potential temperatures between Θ = 35 °C and Θ = 40 °C on Friday, July 22, 1977 at 1200 GMT. Surface positions of the front and high pressure center (H) are shown. Median pressure of the potential temperature surface at the rawinsonde stations is given in millibars.

+ denotes the locations of the two aircraft soundings taken later this day.

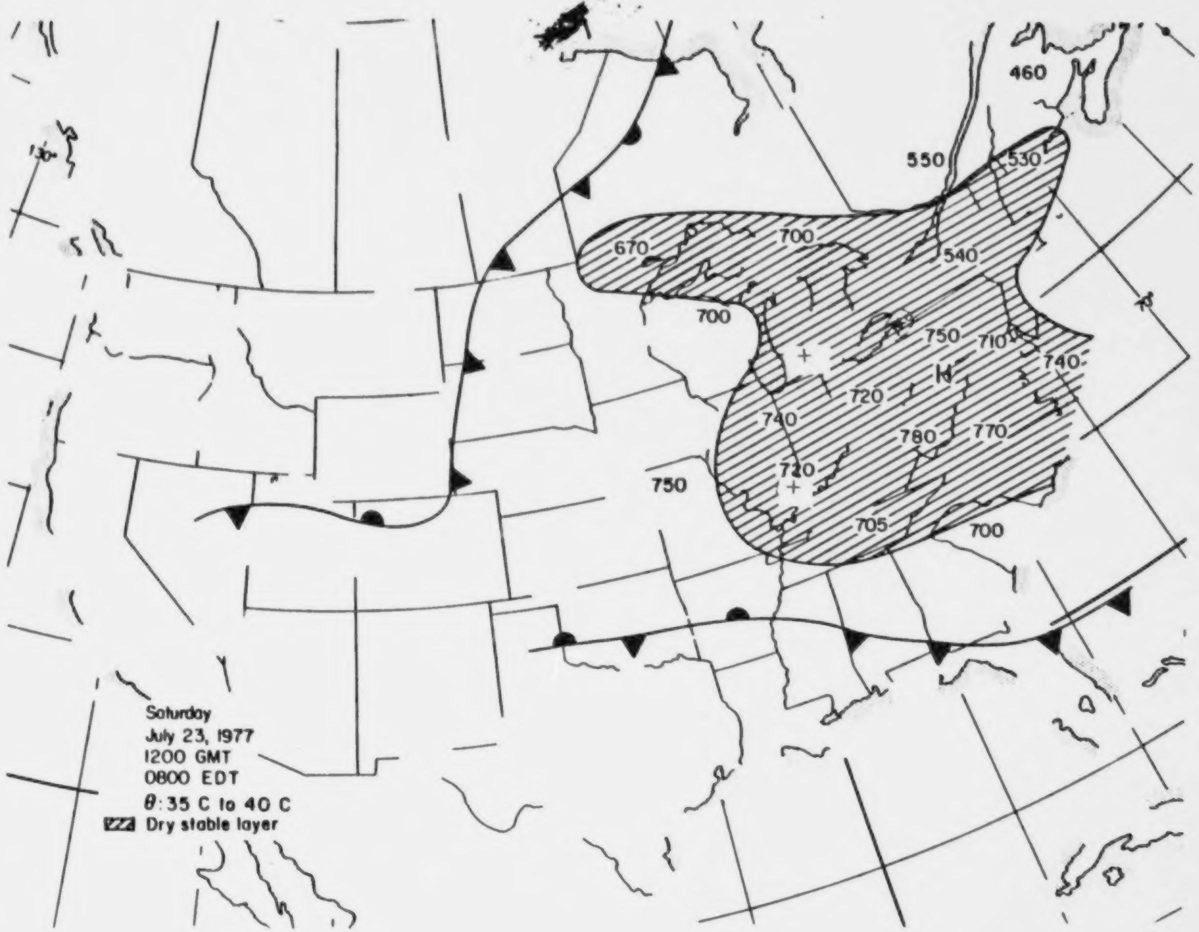


Figure 41. Horizontal extent of dry portion of the stable layer with potential temperatures between Θ = 35 °C and Θ = 40 °C on Saturday, July 23, 1977 at 1200 GMT. There was no moist stable layer at this time. Surface positions of the fronts and high pressure center (H) are shown. Median pressure of the potential temperature surface at the rawinsonde stations is given in millibars.

+ denotes the location of the two aircraft soundings taken later this day.

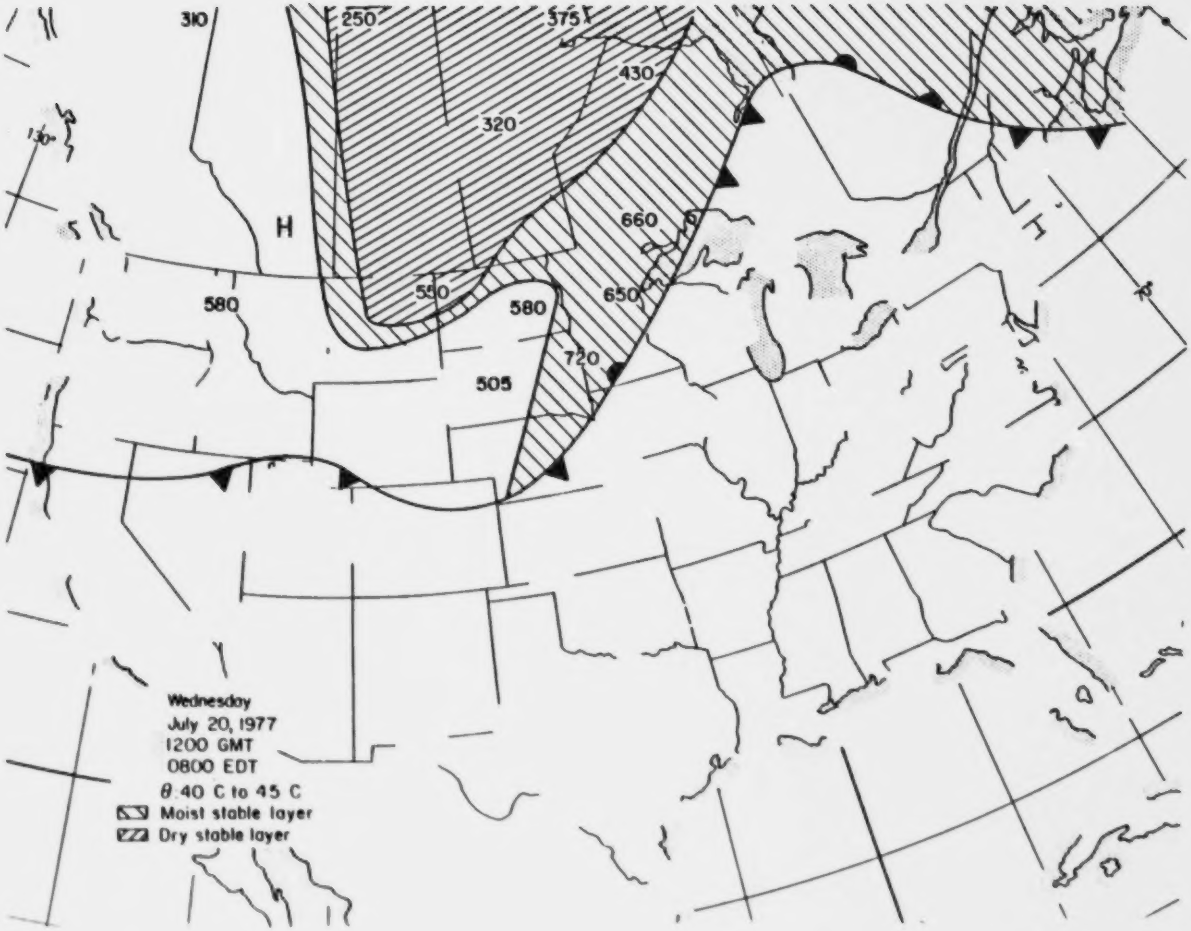


Figure 42. Horizontal extent of moist and dry portions of the stable layer with potential temperatures between Θ = 40 °C and Θ = 45 °C on Wednesday, July 20, 1977 at 1200 GMT. Surface positions of front and high pressure center (H) are shown. Median pressure of the potential temperature surface at the rawinsonde stations is given in millibars.

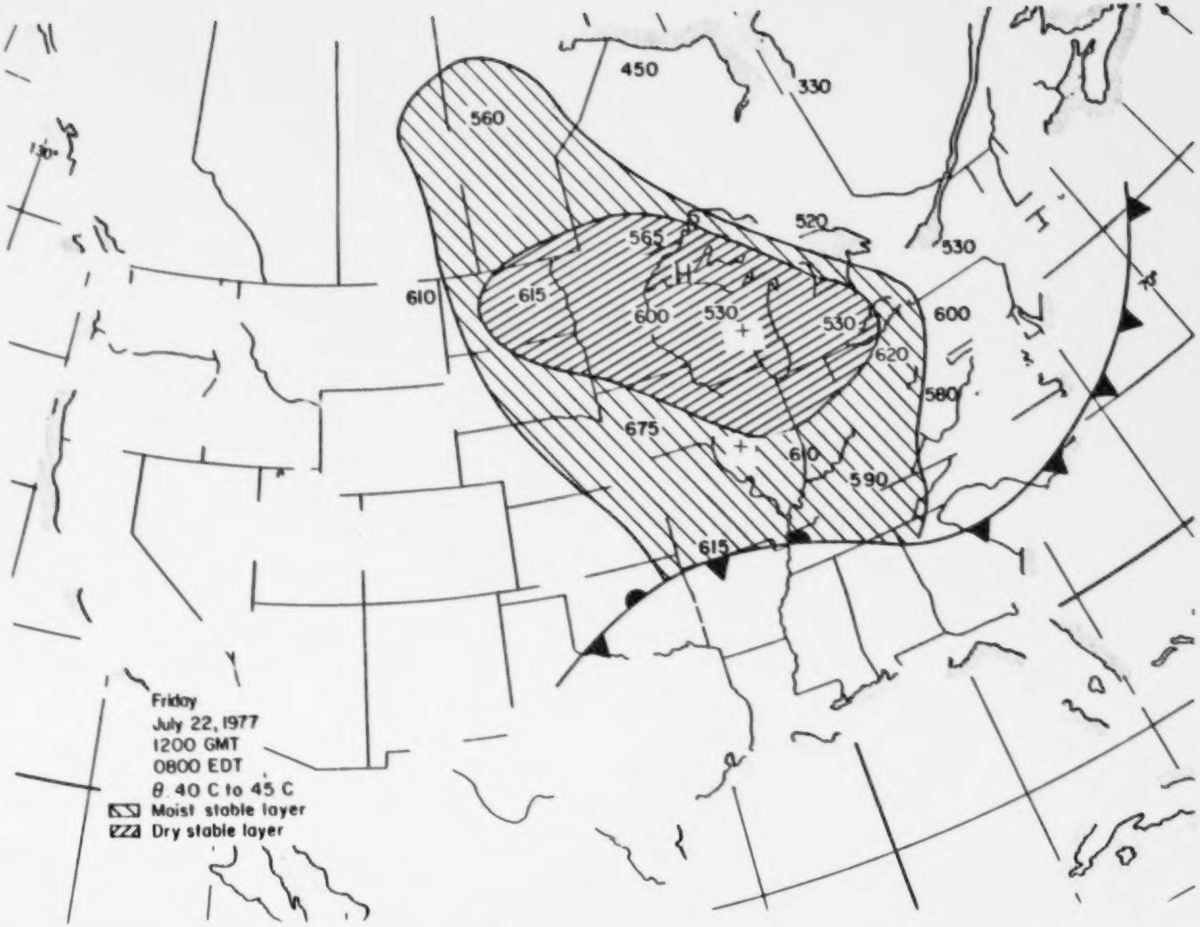


Figure 43. Horizontal extent of moist and dry portions of the stable layer with potential temperatures between Θ = 40 °C and Θ = 45 °C on Friday, July 22, 1977 at 1200 GMT. Surface positions of front and high pressure center (H) are shown. Median pressure of the potential temperature surface at the rawinsonde stations is given in millibars.

+ denotes the locations of the two aircraft soundings taken later this day.

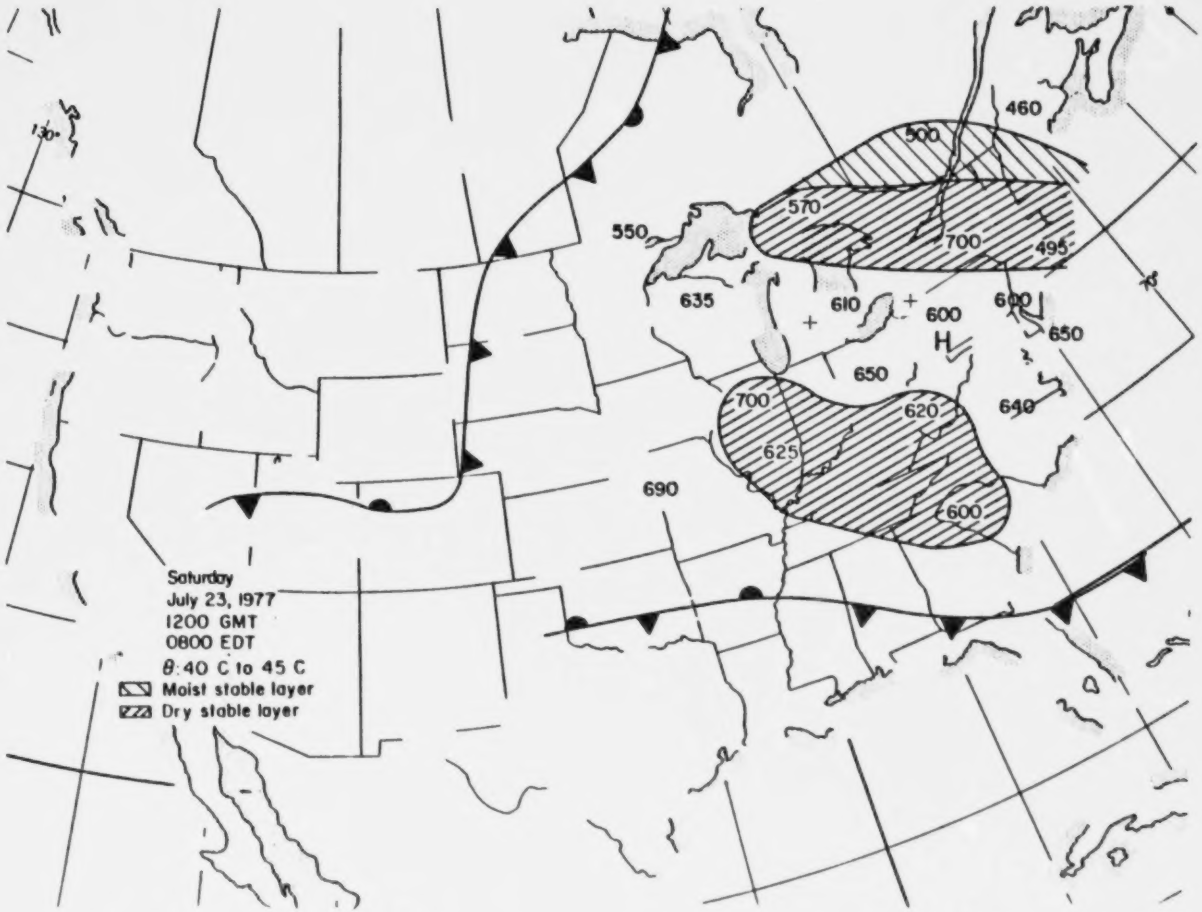


Figure 44. Horizontal extent of moist and dry portions of the stable layer with potential temperatures between $\Theta = 40$ °C and $\Theta = 45$ °C on Saturday, July 23, 1977 at 1200 GMT. Surface positions of front and high pressure center (H) are shown. Median pressure of the potential temperature surface at the rawinsonde stations is given in millibars.

+ denotes the locations of thw two aircraft soundings taken later this day.

From the airplane temperature, humidity, and ozone profiles, one can deduce that most of the soundings penetrated into a portion of the dry stable layer and found ozone there. The one exception was the sounding over central Illinois on the morning of July 22. The dry stable layer on this sounding (Θ = 35C) had no ozone maximum. It did have moist layers below and above it with relative maxima of ozone. As mentioned previously, these ozone maxima are respectively surface generated and air which probably has been modified since its entrance into the troposphere. Figures 37 and 40 indicate that this area of Illinois was in the moist stable layer both at Θ = 25-30C and Θ = 30-35C.

Upon inspection of the dry stable layers on the maps of July 22 and 23, one can deduce that they generally overlay the position of the surface high pressure center, moving with it as it crossed the country.

Based on the upper tropospheric trajectory (Θ = 44C in Figure 32) it appears that after about 4 days the ozone injected from the stratosphere into the upper troposphere lost its identity. The ozone maximum may have persisted, but the air containing it is moist. This result would be similar to the ozone maximum which appeared at 10,000 feet in Figure 24b. The ozone could then be dispersed to become middle-tropospheric background ozone.

Upper Level Cyclogensis and Ozone Injection from the Stratosphere

As was shown in Figure 28, the ozone maximum that was associated with a potential temperature of 44C could be traced backwards from 595 millibars above Green Bay, Wisconsin, at 07:00 CDT on July 23, to a pressure of 300 mb above northern Saskatchewan at 06:00 MDT on July 20. At this latter time the 300 mb level above Saskatchewan was in the stratosphere. Thus the ozone maximum associated with the Θ = 44C stable layer, and identified as stratospheric ozone by its low water vapor mixing ratio and its high potential vorticity, was confirmed as stratospheric by the isentropic trajectory analysis.

Each of the aircraft soundings made in the region behind the cold front observed a second stable layer which generally contained an ozone maximum. This layer was the frontal layer and had a potential temperature in the range of Θ = 25-35C. Isentropic trajectories along the Θ = 30C surface, such as the trajectory shown in Figure 32, paralleled the path of the Θ = 44C trajectory. However, they were well below the tropopause at the time of the stratospheric injection at Θ = 44C (see Figure 29). If the air within the Θ = 30C stable layer originated in the stratosphere, the injection must have occurred at an earlier time and further to the west. During its long trajectory the ozone content and the potential vorticity of this layer dissipated until the parcel could no longer be identified as stratospheric when it had reached the mid United States.

Previous investigators(11, 15-18) of stratospheric injections have shown that the injection occurs during high-level cyclogenesis. In a sequence of 500 mb maps, the time of cyclogenesis can be identified as the time when the trough first contains a low pressure center with the flow around it shown by a closed circle.

By looking at the 500 mb charts for times that are earlier than those shown in Figures 16-22, one can identify the period of cyclogenesis associated with the trough that provided the ozone to the Θ = 30C stable layer. A closed low at 500 mb (17,900 feet) appears above British Columbia on the map for 07:00 EST on July 17 (Figure 45) but is absent on the previous day (Figure 46) and the succeeding day (Figure 16). Confirmation that this period of cyclogenesis is the probable time of injection of the ozone at Θ = 30C is shown in Figure 47, a plot of the rawinsonde sounding temperatures and dewpoints from the ground to 300 mb above Annette Island. Annette Island is off northwestern British Columbia near the southeastern tip of Alaska. On this sounding, made at 07:00 EST on July 17 in the area where cyclogenesis

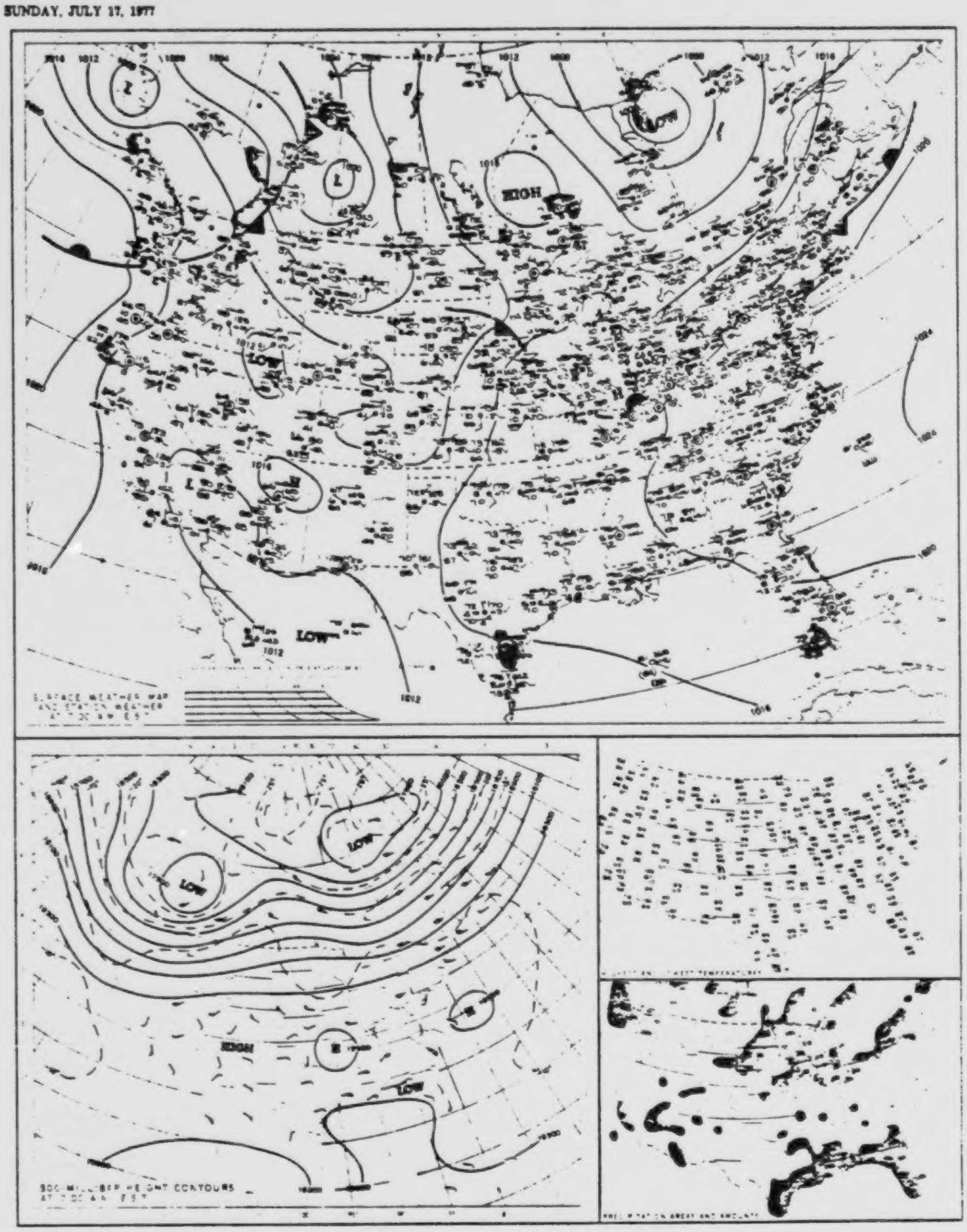


Figure 45. Weather maps for Sunday, July 17, 1977. Top map is the surface map for 7:00 a.m. EST (08:00 EDT). Lower left map is the 500 millibar map for the same time. The right center map displays the maximum and minimum surface temperatures for the previous day. Map in the lower right corner depicts areas and amounts of precipitation (in inches) for the previous day.

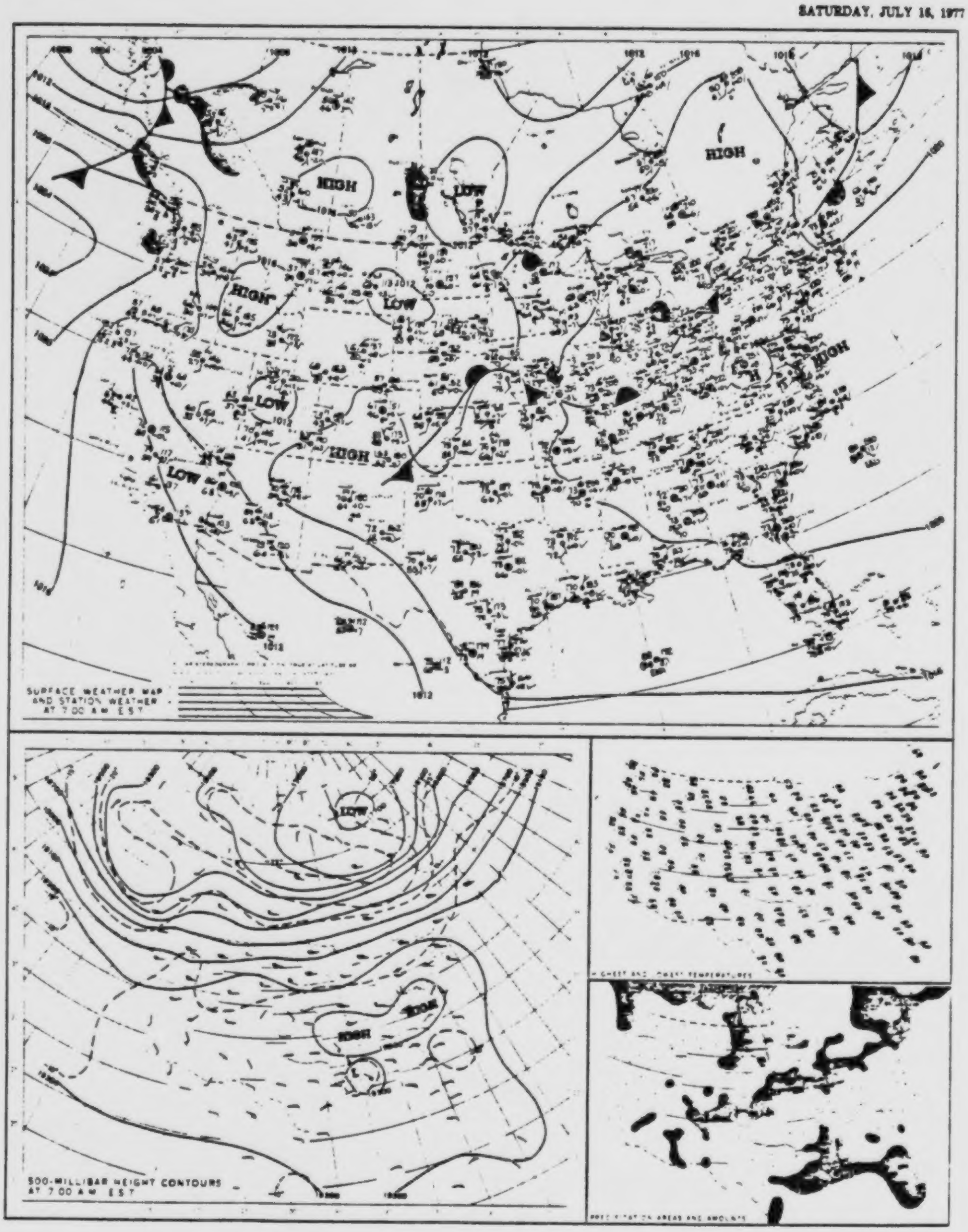

SATURDAY, JULY 16, 1977
HIGH
HIGH
LOW
HIGH
LOW
LOW
HIGH
LOW
HIGH
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
LOW
HIGH
HIGH
500-MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. E.S.T.
HIGHEST AND LOWEST TEMPERATURES
PRECIPITATION AREAS AND AMOUNTS

Figure 46. Weather maps for Saturday, July 16, 1977. Top map is the surface map for 7:00 a.m. EST (08:00 EDT). Lower left map is the 500 millibar map for the same time. The right center map displays the maximum and minimum surface temperatures for the previous day. Map in the lower right corner depicts areas and amounts of precipitation (in inches) for the previous day.

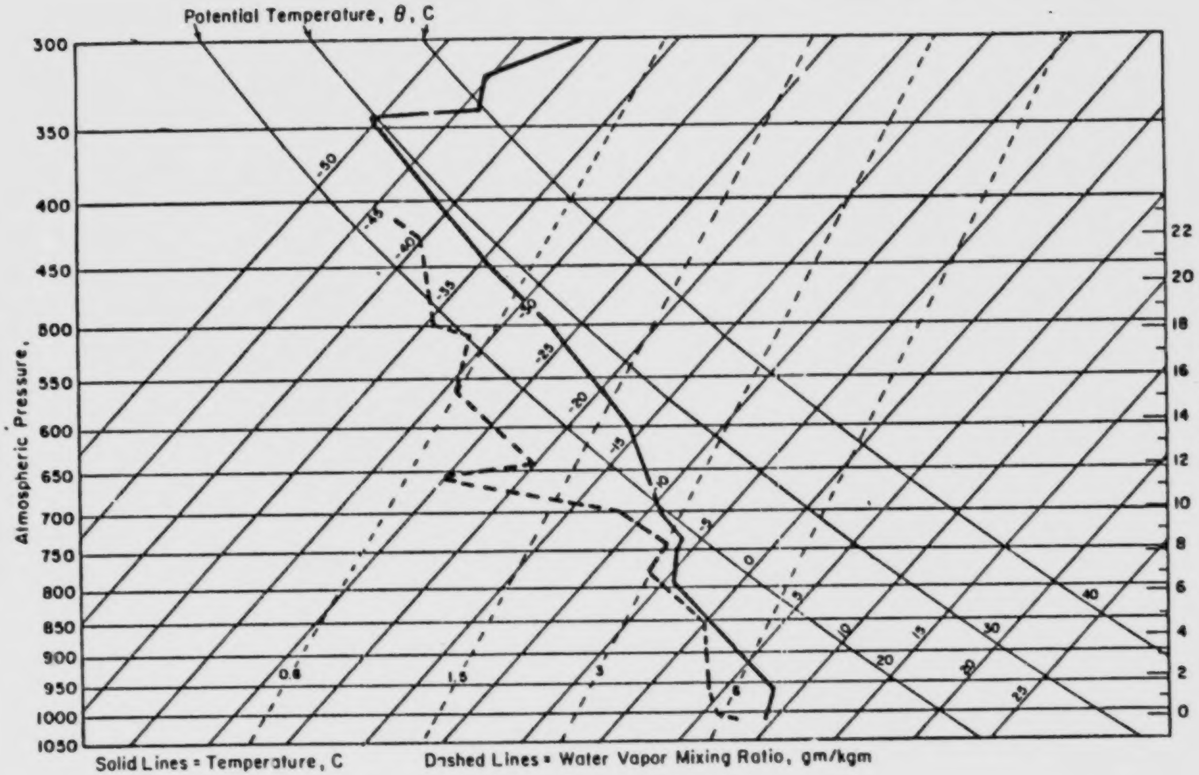


Figure 47. Temperature (solid line) and dewpoint (dashed line) soundings made at the Annette Island, British Columbia, rawinsonde station at 1200 GMT (07:00 CDT) on July 17, 1977. The potential temperature of 30 °C is found at the base of the stratosphere at 345 mb.

was occurring, the tropopause was at a height just above the 350 mb level. On the plot it is clear that the $\Theta = 30C$ surface is within the stratosphere at this place and time. Thus, the ozone appearing in the troposphere within the $\Theta = 30C$ stable layer (the frontal layer) was of stratospheric origin, even though the potential vorticity maxima did not meet the criterion of 10×10^{-9} deg gm^{-1} cm sec in the Great Lakes region.

As mentioned earlier, the trajectory plotting method would have to be refined in order to trace the parcel from the midwest back to Alaska. It would be informative to make calculations of potential vorticity and water vapor mixing ratios at points along the trajectory to see whether their values in western North America met the criteria for stratospheric air. It can be hypothesized that the potential vorticity of the air parcel decreased during the long journey from the Alaskan stratosphere to the Midwest troposphere as a consequence of nonadiabatic processes.

In his study of stratospheric ozone which reached ground level in November, 1972, Lamb(11) showed that the air in a stable layer at about 8000 feet (corresponding to 750 mb) met the potential vorticity and water vapor mixing ratio criteria for stratospheric air. However, the horizontal distance covered by Lamb's stable layer between the stratosphere and 750 mb was considerably less than the horizontal distances discussed here. It is likely that the potential vorticity, water vapor mixing ratio, and ozone characteristics of the 1977 $\Theta = 30C$ layer, if measured in the northwest U.S. on July 17 or 18, would be stronger indicators of stratospheric air than was the case for this layer when it reached the Midwest.

Summary of the Spiral Sounding Investigation--

Based upon the sounding results and the associated analyses for this July, 1977, high pressure area investigation, there are several points to be emphasized.

(1) Ozone was injected from the stratosphere into the the troposphere along a stable frontal layer at the time of upper air cyclogenesis when the height of the tropopause was a minimum.

(2) The injection along the frontal layer took place over northwest Canada-southeast Alaska. The injection was limited in time so

that the ozone remained as a finite layer when it later appeared above the surface high pressure area in the Midwest.

(3) The ozone in the frontal layer did not extend to the ground in the Midwest and thus there was no rise in ozone at the surface marking the frontal passage.

(4) The frontal stable layer was also the subsidence inversion overlying the high pressure area. On the backside of the high pressure area the stratospheric ozone within this inversion layer could be distinguished from the anthropogenic ozone which filled the layer from the ground to the base of the inversion.

(5) As a new front passes, it may have stratospheric ozone within its stable layer wedging a path beneath a deep layer of aged anthropogenic ozone.

(6) In addition to the ozone in the frontal stable layer, there were ozone layers above the frontal/subsidence inversion. These upper ozone maxima were the result of injections from the stratosphere at higher altitudes and at later times than the frontal layer injection. All of these layers were originally created when a finite amount of ozone was injected from the stratosphere. These ozone areas retained their finite extent as they subsided through the troposphere. These upper ozone layers, like the ozone in the frontal layer, were loosely centered above the surface high pressure area as it moved across the country.

(7) Each finite area of high ozone concentration within its stable layer retained its downward slope from northwest to southeast as it progressed across the Midwest from west to east.

Observations made during the cross-country traverse of this July high pressure area lead to the conclusion that layers of stratospheric ozone with concentrations in excess of the surface ambient standard can be found in the troposphere above a high pressure area, but that the ozone in these layers has no direct effect on the surface concentrations in the Midwest during the summer.

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APPENDIX A

GROUND STATION DATA FROM 1977 MIDWEST FIELD PROGRAM

The data in Appendix A are hourly averages from the Bethalto, Illinois ground site covering the period July 7 to August 3, 1977. Study averages are given on page A-24. The symbol -1.0 indicates missing data. A negative sign for any other value indicates an interpolated value.

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                              BETHALTO, ILL.

                              JULY    7, 1977


                        10         11         12         13         14         15         16         17         18         19         20         21
IRAD - LANGLEY/M    -1.000     -1.000     -1.000     -1.000       .897       .826       .725       .612       .448       .280       .119       .023
WIND SPEED - MPH    -1.00      -1.00      -1.00      -1.00      -1.00      -1.00      -1.00      -1.00      -1.00       8.40       8.17       7.00
WIND DIR - DEG      -1.        -1.        -1.        -1.        -1.        -1.        -1.        -1.        -1.        225.       223.       230.
TEMP - DEG C        -1.0       -1.0       -1.0       -1.0       35.9       36.6       37.1       37.1       36.5       35.5       33.7       31.9
RH - %              -1.0       -1.0       -1.0       -1.0       61.6       59.0       58.3       56.3       56.8       59.1       63.1       67.5
O3 - PPM            -1.000     -1.000     -1.000     -1.000       .082       .087       .078       .087       .102       .108       .068       .062
NO - PPM            -1.000     -1.000     -1.000     -1.000    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005
NOX - PPM           -1.000     -1.000     -1.000     -1.000       .005    ≤  .005       .010       .011       .007       .009    ≤  .005       .007
HNO3 - PPM          -1.000     -1.000     -1.000    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
FREON 11 -PPT       -1.        -1.        -1.        -1.        -1.        -1.        -1.        328.       289.       203.       235.       215.


                        22         23         24          1          2          3          4          5          6          7          8          9
IRAD - LANGLEY/M      .015       .015       .015       .014       .014       .015       .016       .014       .015       .063       .205       .380
WIND SPEED - MPH     5.93       4.63       3.60       3.50       2.33       4.03       2.77       1.60       2.80       2.00       3.37       4.20
WIND DIR - DEG      219.       226.       197.       220.       236.       186.       60.        107.       195.       219.       263.       158.
TEMP - DEG C         30.8       29.8       28.9       28.3       28.1       27.0       24.9       23.9       23.3       24.8       26.0       28.6
RH - %               71.6       76.0       80.9       84.7       85.8       90.3       94.4       92.9       93.9       92.4       88.1       81.0
O3 - PPM              .045       .027       .024       .010       .009       .024       .029       .035       .028       .022       .028       .034
NO - PPM            ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005
NOX - PPM             .017       .019       .016       .026       .026    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005
HNO3 - PPM          ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
FREON 11 -PPT       252.       250.       321.       354.       418.       366.       220.       285.       189.       206.       230.       226.

      DAILY AVERAGE

IRAD - LANGLEY/M      .236
WIND SPEED - MPH     4.29
WIND DIR - DEG      197.
TEMP - DEG C         30.4
RH - %               75.7
O3 - PPM              .049
NO - PPM            ≤  .005
NOX - PPM             .009
HNO3 - PPM          ≤  .006
FREON 11 -PPT       270.
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BETHALTO, ILL.

JULY   8, 1977

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                      10          11          12          13          14          15          16          17          18          19          20          21
IRAD - LANGLEY/M      .540        .686        .892        .867        .628        .644        .081        .247        .405        .122        .090        .020
WIND SPEED - MPH     1.77        6.47        5.37        7.13        4.47        5.40        2.50         .10         .17       -1.00       -1.00       -1.00
WIND DIR - DEG     125.        235.        250.        224.        182.        130.        289.        108.         64.         -1.         -1.         -1.
TEMP - DEG C        30.7        30.8        32.9        33.1        32.8        32.7        25.9        24.5        28.1        27.3        27.1        25.9
RH - %              75.9        75.2        69.1        70.2        71.2        65.4        86.7        99.1        87.7        87.5        87.8        89.8
O3 - PPM              .057        .029        .055        .076        .073        .065        .049        .047        .054        .047        .042        .037
NO - PPM           ≤  .005        .018   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005
NOX - PPM             .009        .063        .035        .023        .006        .006        .018        .014        .007        .010        .009        .010
HNO3 - PPM         ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
FREON 11 -PPT      325.        322.        233.        227.        213.        257.        211.        223.        150.        158.        117.       -134.

                      22          23          24           1           2           3           4           5           6           7           8           9
IRAD - LANGLEY/M      .012        .013        .012        .012        .013        .013        .013        .013        .013        .038        .169        .397
WIND SPEED - MPH    -1.00       -1.00       -1.00       -1.00       -1.00       -1.00       -1.00       -1.00       -1.00       -1.00       -1.00       -1.00
WIND DIR - DEG      -1.         -1.         -1.         -1.         -1.         -1.         -1.         -1.         -1.         -1.         -1.         -1.
TEMP - DEG C        25.3        24.9        23.7        22.9        22.5        22.2        21.9        21.8        21.9        21.9        23.1        25.4
RH - %              93.8        95.5        93.3        94.9        96.5        98.3        99.1        98.9        97.9        96.2        93.3        88.2
O3 - PPM              .027        .016        .039        .038        .036        .029        .029        .028        .025        .027        .032        .033
NO - PPM           ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005
NOX - PPM             .012        .019   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005
HNO3 - PPM         ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
FREON 11 -PPT     -150.       -166.        183.        202.        191.        194.        201.        337.        242.        275.        192.        189.

     DAILY AVERAGE

IRAD - LANGLEY/M      .247
WIND SPEED - MPH     3.71
WIND DIR - DEG     178.
TEMP - DEG C        26.2
RH - %              88.0
O3 - PPM              .041
NO - PPM           ≤  .005
NOX - PPM             .010
HNO3 - PPM         ≤  .006
FREON 11 -PPT      212.
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BETHALTO, ILL.

JULY 9, 1977

	10	11	12	13	14	15	16	17	18	19	20	21
IRAD - LANGLEY/M	.575	.716	.859	.893	.846	.800	.753	.643	.484	.312	.130	.024
WIND SPEED - MPH	-1.00	-1.00	-1.00	6.60	-6.13	-5.67	5.20	7.57	9.57	8.60	6.77	3.80
WIND DIR - DEG	-1.	-1.	-1.	57.	-55.	-53.	51.	54.	52.	58.	51.	50.
TEMP - DEG C	26.6	28.2	29.0	30.1	-30.7	-31.2	31.8	31.9	31.7	30.7	29.6	27.1
RH - %	84.6	77.9	76.1	65.8	-64.2	-62.5	60.9	59.4	59.2	58.8	61.9	69.7
O3 - PPM	.040	.053	.064	.074	.078	.078	.080	.081	.080	.083	.088	.075
NO - PPM	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	< .005	< .005	≤ .005
NOX - PPM	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	< .005	≤ .005	.008
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	< .006	≤ .006	≤ .006
FREON 11 -PPT	270.	161.	178.	216.	217.	180.	-178.	175.	175.	190.	208.	176.

	22	23	24	1	2	3	4	5	6	7	8	9
IRAD - LANGLEY/M	.012	.011	.011	.011	.012	.012	.012	.012	.013	.051	.157	.272
WIND SPEED - MPH	2.77	3.07	2.83	4.47	5.97	6.63	6.37	3.80	4.30	5.20	3.40	1.97
WIND DIR - DEG	51.	58.	70.	54.	60.	49.	50.	140.	36.	51.	35.	151.
TEMP - DEG C	25.6	24.4	23.9	24.2	24.1	23.0	21.9	20.8	20.0	19.9	20.9	23.9
RH - %	76.6	81.2	83.6	84.8	89.4	94.5	96.0	95.8	96.0	94.5	90.3	81.4
O3 - PPM	.055	.045	.036	.050	.064	.058	.045	.036	.029	.025	.024	.027
NO - PPM	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005
NOX - PPM	.016	.013	.014	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	< .005	< .005	≤ .005
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	< .006	≤ .006	≤ .006
FREON 11 -PPT	247.	272.	402.	268.	187.	203.	195.	131.	131.	148.	155.	155.

DAILY AVERAGE

IRAD - LANGLEY/M	.318
WIND SPEED - MPH	5.27
WIND DIR - DEG	61.
TEMP - DEG C	26.3
RH - %	77.7
O3 - PPM	.057
NO - PPM	≤ .005
NOX - PPM	≤ .005
HNO3 - PPM	≤ .006
FREON 11 -PPT	201.

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                         BETHALTO, ILL.

                         JULY   11, 1977


                        10         11         12         13         14         15         16         17         18         19         20         21
IRAD - LANGLEY/M      .223       .091       .181       .259       .396       .559       .667      -.536      -.404       .273       .131       .032
WIND SPEED - MPH     3.33       3.27       1.40        .93       2.20       2.47       2.43      -2.42      -2.41       2.40       1.50       1.63
WIND DIR - DEG     139.       262.       283.       124.       144.        89.        53.        -88.      -122.       157.        90.       229.
RH - %             101.6      103.8      103.8      103.7       97.3       86.9       76.2      -74.4      -72.5       70.7       76.0       87.6
O3 - PPM              .027       .029       .054       .050       .049       .053       .052      -.059      -.065       .072       .062       .038
NO - PPM           ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005
NOX - PPM          ≤  .005    ≤  .005       .009    ≤  .005    ≤  .005    ≤  .005    ≤  .005      -.006      -.013       .019       .012       .019
HNO3 - PPM         ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
PAN - PPM           -1.0       -1.0       -1.0       -1.0       -1.0       -1.0          .002       .002       .002      -.002    ≤ -.001    ≤ -.001
FREON 11 -PPT      248.       186.       838.       820.       332.       231.       220.       417.       374.       290.        -1.        -1.
CO - PPM              .66        .55        .64        .72        .51        .64        .38       -.41       -.43        .46        .30        .36


                        22         23         24          1          2          3          4          5          6          7          8          9
IRAD - LANGLEY/M      .020       .018       .016       .017       .016       .015       .015       .016       .011       .018       .059       .263
WIND SPEED - MPH     1.63       1.53        .80       2.13       6.37       5.07       5.33      11.70       7.57       6.80       8.37       3.20
WIND DIR - DEG     177.       203.       107.       200.       173.       227.       210.       195.       184.       178.       215.       160.
RH - %              94.3       95.3       97.9       97.1       97.1       99.9      103.6       95.3      101.1       97.0       92.8       89.9
O3 - PPM              .030       .020       .019       .012       .026       .020       .011       .023       .028       .029       .025       .023
NO - PPM           ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005       .009
NOX - PPM             .014       .015       .013       .026       .017       .019       .025       .022       .020       .015       .022       .034
HNO3 - PPM         ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
PAN - PPM          ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001       .002       .002    ≤  .001    ≤  .001       .002    ≤  .001    ≤  .001
FREON 11 -PPT       -1.        -1.        -1.        -1.        -1.        -1.        -1.        -1.        -1.        -1.       660.       660.
CO - PPM              .28        .28        .28        .41        .52        .43        .73        .27        .14        .20        .25        .41


      DAILY AVERAGE

IRAD - LANGLEY/M      .176
WIND SPEED - MPH     3.62
WIND DIR - DEG     167.
RH - %              92.3
O3 - PPM              .036
NO - PPM           ≤  .005
NOX - PPM             .014
HNO3 - PPM         ≤  .006
PAN - PPM           -1.0
FREON 11 -PPT      440.
CO - PPM              .43
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                                   BETHALTO, ILL.

                                   JULY   12, 1977


                     10        11        12        13        14        15        16        17        18        19        20        21
IRAD - LANGLEY/M    .349      .494      .718      .914      .898      .826      .729      .615      .454      .233     -.165      .036
WIND SPEED - MPH   5.04     -5.98     -6.92     -7.86      8.60      9.10      7.00      7.57      5.60      6.60     -5.30      4.00
WIND DIR - DEG    220.      -229.     -238.     -247.      256.      231.      253.      257.      262.     -246.     -230.      21[illegible].
RH - %             75.5      71.0      67.0      63.3      58.0      57.7      57.5      56.7      58.9     -62.2     -65.5      68.8
O3 - PPM            .037      .045      .050      .065      .067      .072      .068      .069     -.068      .066     -.051      .036
NO - PPM         ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005
NOX - PPM           .030      .022      .016      .011      .014      .017      .012      .014     -.019     -.024     -.028      .033
HNO3 - PPM       ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
PAN - PPM          -.002     -.004      .006      .002      .002   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001      .002      .002
FREON 11 -PPT    1068.      272.      223.      284.      451.      264.      120.     -178.     -235.      293.      156.      240.
CO - PPM           -.74      1.07      2.19      2.11      2.01       .53       .25       .24      -.32       .40      -.97      1.54


                     22        23        24         1         2         3         4         5         6         7         8         9
IRAD - LANGLEY/M    .021      .018      .018      .016      .016      .015      .014      .014      .016      .015      .182      .361
WIND SPEED - MPH   3.77      3.53      3.47      4.40      4.13      4.27      3.33      3.37      2.37      1.30      1.80      3.00
WIND DIR - DEG    169.      170.      176.      183.      189.      190.      181.      182.      201.      225.      223.      302.
RH - %             73.7      77.2      78.7      84.0      89.3      93.5      96.8      98.3      97.9      97.7      92.2      84.6
O3 - PPM            .022      .015      .015      .006   ≤  .002   ≤  .002   ≤  .002   ≤  .002   ≤  .002      .006      .026      .044
NO - PPM            .005   ≤  .005   ≤  .005   ≤  .005      .011      .014      .015      .007   ≤  .005   ≤  .005   ≤  .005   ≤  .005
NOX - PPM           .030      .026      .028      .033      .045      .045      .043      .035      .039      .037      .024      .007
HNO3 - PPM       ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
PAN - PPM           .002      .002    -1.000    -1.000    -1.000    -1.000    -1.000    -1.000    -1.000    -1.000    -1.000    -1.000
FREON 11 -PPT     379.      700.      460.      400.      500.      500.      475.      400.      350.      300.      350.      450.
CO - PPM            .90       .75       .56       .69       .94      1.02       .85       .66       .69       .87      1.42      3.02


        DAILY AVERAGE

IRAD - LANGLEY/M      .300
WIND SPEED - MPH     4.94
WIND DIR - DEG     220.
RH - %              76.1
O3 - PPM              .035
NO - PPM           ≤  .005
NOX - PPM             .026
HNO3 - PPM         ≤  .006
PAN - PPM             .002
FREON 11 -PPT      377.
CO - PPM             1.03
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                      BETHALTO, ILL.

                      JULY   13, 1977


                     10         11         12         13         14         15         16         17         18         19         20         21
IRAD - LANGLEY/M    .548       .669       .812       .882       .853       .636       .287       .297       .073       .342       .097       .029
WIND SPEED - MPH   3.04       5.97       4.17       3.43       5.40       4.23       4.33       9.50       7.97       3.70       2.63       3.27
WIND DIR - DEG   267.       265.       257.       197.       229.       210.       146.       181.       286.       256.       157.       134.
TEMP - DEG C      -1.0       -1.0       -1.0       -1.0       38.3       38.8       39.1       37.2       28.4       33.6       32.9       30.6
RH - %            78.7       71.7       67.4       61.3       58.4       57.0       58.3       61.4       73.8       71.6       71.7       80.6
O3 - PPM            .068       .074       .085       .075       .061       .116       .155       .100       .054       .058       .040       .039
NO - PPM         ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005
NOX - PPM           .006       .009    ≤  .005       .016       .021    ≤  .005    ≤  .005    ≤  .005       .012       .017       .026       .010
HNO3 - PPM       ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
PAN - PPM        ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001
FREON 11 -PPT    263.       526.       614.       329.       175.      -230.      -286.       341.       370.       244.        -1.        -1.
CO - PPM           6.69       8.46       8.63       7.13       5.64       4.43       3.15       2.22       1.25       1.20       1.46        .92


                     22         23         24          1          2          3          4          5          6          7          8          9
IRAD - LANGLEY/M    .020       .019       .018       .015       .016       .014       .015       .014       .014       .014       .200       .379
WIND SPEED - MPH   2.97       6.30       6.40       5.97       4.80       2.43       2.87       1.60       1.63       2.83       3.17       4.23
WIND DIR - DEG   133.       176.       182.       175.       168.       152.       216.       201.       161.       148.       208.       182.
TEMP - DEG C      29.4       30.2       29.8       29.4       29.0       27.9       27.6       26.7       26.3       26.9       30.2       31.5
RH - %            84.6       84.7       87.2       88.3       88.4       91.2       92.0       95.2       97.1       97.1       89.8       80.3
O3 - PPM            .032       .029       .004    ≤  .002    ≤  .002       .004       .003    ≤  .002    ≤  .002       .008       .047       .078
NO - PPM         ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005       .003    ≤  .005    ≤  .005    ≤  .005
NOX - PPM           .006    ≤  .005       .023       .026       .028       .019       .026       .027       .033       .022       .020       .026
HNO3 - PPM       ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
PAN - PPM        ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001    ≤  .001       .002       .005       .005
FREON 11 -PPT     -1.        -1.        -1.        -1.        -1.        -1.        -1.        -1.        -1.        -1.        -1.      3049.
CO - PPM            .76        .51       1.27       1.37       1.83       1.16       1.59       1.35       1.14        .82       1.19       1.07


      DAILY AVERAGE

IRAD - LANGLEY/M      .261
WIND SPEED - MPH     4.28
WIND DIR - DEG     195.
TEMP - DEG C        31.2
RH - %              78.7
O3 - PPM              .047
NO - PPM           ≤  .005
NOX - PPM             .016
HNO3 - PPM         ≤  .006
PAN - PPM          ≤  .001
FREON 11 -PPT      564.
CO - PPM             2.72
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                        BETHALTO, ILL.

                        JULY   14, 1977


                        10         11         12         13         14         15         16         17         18         19         20         21
IRAD - LANGLEY/M      .523       .663       .797       .884       .870       .415       .704       .560       .418       .259       .112       .032
WIND SPEED - MPH     4.33       6.63       5.37       8.80       8.13       7.93       8.70       7.33       8.13       8.97       5.80       3.83
WIND DIR - DEG     167.       189.       208.       206.       207.       158.       152.       143.       161.       167.       163.       151.
TEMP - DEG C        34.3       34.1       35.6       36.2       37.1       39.1       40.4       40.2       40.6       39.6       36.1       32.5
RH - %              73.1       72.0       65.8       60.8       57.9       54.1       50.4       51.8       52.4       54.3       60.3       70.0
O3 - PPM              .093       .131       .159       .118       .143       .116       .103       .102       .098       .090       .079       .065
NO - PPM           ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    <  .005    ≤  .005    ≤  .005
NOX - PPM             .036       .031       .008    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005
HNO3 - PPM         ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
PAN - PPM             .005       .006       .009       .008       .009       .009       .008    -1.000     -1.000     -1.000     -1.000     -1.000
FREON 11 -PPT      257.       670.       661.       378.       297.       201.       105.       110.       108.       150.       154.       200.
CO - PPM             1.44       1.87       2.07       1.30       1.40       1.11        .85        .82        .72        .56        .49        .59


                        22         23         24          1          2          3          4          5          6          7          8          9
IRAD - LANGLEY/M      .020       .019       .016       .016       .015       .016       .014       .015       .013       .016       .164       .331
WIND SPEED - MPH     2.07       3.40       4.57       4.07       3.07       2.03       2.93       2.07        .70       1.33       1.63       3.72
WIND DIR - DEG     133.       160.       166.       182.       185.       227.       189.       123.        64.       110.       129.       165.
TEMP - DEG C        31.0       30.2       29.8       29.0       28.3       27.9       27.5       26.6       25.7       26.7       30.3       32.1
RH - %              78.3       81.8       82.6       86.6       89.5       90.9       91.9       93.7       97.9       96.2       88.9       80.1
O3 - PPM              .051       .045       .039       .012       .005       .004    ≤  .002    ≤  .002    ≤  .002    ≤  .002       .006       .034
NO - PPM           ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005
NOX - PPM             .005       .006    ≤  .005       .022       .028       .022       .027       .023       .014       .011       .009       .025
HNO3 - PPM         ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
PAN - PPM          -1.000     -1.000     -1.000     -1.000     -1.000     -1.000     -1.000     -1.000     -1.000     -1.000     -1.000     -1.000
FREON 11 -PPT      204.       152.       114.       242.       135.       123.       155.       141.       279.       354.       214.       231.
CO - PPM              .54        .52        .56       1.03       1.12       1.02       1.05        .83        .62        .55        .55       1.03


      DAILY AVERAGE

IRAD - LANGLEY/M      .287
WIND SPEED - MPH     4.81
WIND DIR - DEG     163.
TEMP - DEG C        33.0
RH - %              74.2
O3 - PPM              .062
NO - PPM           ≤  .005
NOX - PPM             .012
HNO3 - PPM         ≤  .006
PAN - PPM             .006
FREON 11 -PPT      235.
CO - PPM              .94
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                        BETHALTO, ILL.

                        JULY   15, 1977


                      10         11         12         13         14         15         16         17         18         19         20         21
IRAD - LANGLEY/M     .489       .628       .605       .376       .363       .317       .574       .526       .298       .049       .038       .023
WIND SPEED - MPH    5.37       3.40       4.00       4.50       4.80       7.93       5.33       7.03       4.80       2.57       2.57       3.80
WIND DIR - DEG    214.       226.       259.       182.       158.       165.       150.       154.       138.       138.       143.       177.
TEMP - DEG C       32.6       35.2       36.0       35.3       36.6       37.5       38.9       39.1       38.1       35.1       32.9       31.8
RH - %             77.6       70.2       63.9       64.0       59.7       58.0       55.7       55.5       58.2       63.6       70.8       75.7
O3 - PPM             .120       .133       .133       .150       .131       .110       .096       .096       .092       .086       .080       .061
NO - PPM          ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005
NOX - PPM            .032       .022       .010       .025       .014       .006    ≤  .005    ≤  .005    ≤  .005    ≤  .005       .008       .011
HNO3 - PPM        ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
FREON 11 -PPT     278.       236.       158.       292.       274.       140.       132.      -132.       132.       170.       120.       126.
CO - PPM            1.08       1.16        .89        .87        .78        .52        .39       -.51       -.64        .76        .53        .25



                      22         23         24          1          2          3          4          5          6          7          8          9
IRAD - LANGLEY/M     .018       .017       .014       .015       .015       .014       .015       .013       .013       .019       .130       .325
WIND SPEED - MPH    2.80       2.33       2.83       4.20       2.83       2.10       1.80       1.80       1.27       1.87       2.70       2.80
WIND DIR - DEG    153.       121.       164.       181.       200.       223.       215.        65.       162.        82.       100.       159.
TEMP - DEG C       30.6       30.6       29.6       28.9       28.4       27.6       27.0       25.7       25.3       25.4       28.0       30.8
RH - %             79.8       80.4       83.6       81.2       80.4       83.0       86.2       93.4       96.3       96.6       91.1       81.4
O3 - PPM             .034       .042       .030       .010       .003    ≤  .002    ≤  .002    ≤  .002    ≤  .002    ≤  .002       .011       .055
NO - PPM          ≤  .005    ≤  .005    ≤  .005    ≤  .005    ≤  .005       .012       .020       .015       .011       .019       .016    ≤  .005
NOX - PPM            .028       .014       .015       .027       .039       .046       .055       .035       .029       .033       .017       .020
HNO3 - PPM        ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006    ≤  .006
FREON 11 -PPT     229.       277.       100.       100.       132.       226.       282.       247.       239.       235.       330.       262.
CO - PPM          ≤  .10     ≤  .10     ≤  .10     ≤  .10     ≤  .10     ≤  .10     ≤  .10     ≤  .10     ≤  .10     ≤  .10     ≤  .10     ≤  .10


     DAILY AVERAGE

IRAD - LANGLEY/M     .206
WIND SPEED - MPH    3.56
WIND DIR - DEG    164.
TEMP - DEG C       32.0
RH - %             75.3
O3 - PPM             .061
NO - PPM          ≤  .005
NOX - PPM            .020
HNO3 - PPM        ≤  .006
FREON 11 -PPT     202.
CO - PPM             .35
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                          BETHALTO. ILL.

                          JULY   16. 1977

                     10        11        12        13        14        15        16        17        18        19        20        21
IRAD - LANGLEY/M    .491      .594      .667      .798      .660      .360      .374      .315      .188      .166      .075      .027
WIND SPEED - MPH   3.13      3.40      3.73      7.33      5.60      5.70      5.53      8.23      5.50      7.63      6.43      4.47
WIND DIR - DEG   230.      201.      227.      208.      175.      158.      153.      165.      158.      165.      167.      157.
TEMP - DEG C      31.6      33.5      35.3      35.6      36.8      37.4      37.5      37.5      36.1      34.9      33.2      31.5
RH - %            78.3      72.4      65.1      60.3      58.9      58.6      58.4      58.3      60.7      64.3      67.3      69.6
O3 - PPM            .118      .122      .118      .109      .136      .142      .106      .093      .086      .095      .077      .062
NO - PPM         ≤  .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005
NOX - PPM           .015      .024      .016      .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005
HNO3 - PPM       ≤  .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006
PAN - PPM           .003      .003      .005      .002      .002      .002      .002  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001
FREON 11 -PPT      -1      -209.     -275.     -342.    ≤ -1       408.      464.      229.      161.      146.      192.      309.
CO - PPM            .62       .74       .59       .47       .63       .61       .36       .32       .34       .33       .29       .31


                     22        23        24         1         2         3         4         5         6         7         8         9
IRAD - LANGLEY/M    .018      .018      .015      .014      .013      .014      .014   -1.000    -1.000    -1.000    -1.000    -1.000
WIND SPEED - MPH   3.37      4.47      4.30      3.93      3.77      2.37      1.47    -1.00     -1.00     -1.00     -1.00     -1.00
WIND DIR - DEG   165.      177.      183.      165.      172.       70.      164.      -1.       -1.       -1.       -1.       -1.
TEMP - DEG C      29.9      29.3      29.0      28.1      27.5      26.1      25.6     -1.0      -1.0      -1.0      -1.0      -1.0
RH - %            75.5      79.3      82.4      87.4      89.1      94.5      97.1     -1.0      -1.0      -1.0      -1.0      -1.0
O3 - PPM            .045      .032      .018      .011      .005      .003      .006   -1.000    -1.000    -1.000    -1.000    -1.000
NO - PPM         ≤  .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005   -1.000    -1.000    -1.000    -1.000    -1.000
NOX - PPM        ≤  .005      .011      .020      .020      .027      .022      .010   -1.000    -1.000    -1.000    -1.000    -1.000
HNO3 - PPM       ≤  .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006   -1.000    -1.000    -1.000    -1.000    -1.000
PAN - PPM        ≤  .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001   -1.000    -1.000    -1.000    -1.000    -1.000
FREON 11 -PPT    295.      171.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.
CO - PPM            .36       .56       .67       .91       .91       .83       .63    -1.00     -1.00     -1.00     -1.00     -1.00


     DAILY AVERAGE

IRAD - LANGLEY/M      .254
WIND SPEED - MPH     4.76
WIND DIR - DEG     171.
TEMP - DEG C        32.4
RH - %              72.5
O3 - PPM              .073
NO - PPM           ≤  .005
NOX - PPM             .009
HNO3 - PPM         ≤  .006
PAN - PPM          ≤  .001
FREON 11 -PPT      229.
CO - PPM              .55
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BETHALTO, ILL.

JULY 18, 1977

	10	11	12	13	14	15	16	17	18	19	20	21
IRAD - LANGLEY/M	-1.000	.668	.791	.872	.857	.739	.686	.326	.135	.252	.106	.028
WIND SPEED - MPH	-1.00	8.77	9.27	9.27	8.57	4.13	5.47	6.00	5.63	1.93	3.17	4.13
WIND DIR - DEG	-1.	229.	160.	236.	244.	212.	218.	151.	163.	213.	85.	126.
TEMP - DEG C	-1.0	32.1	34.0	35.1	35.7	36.7	37.2	37.8	31.4	33.5	31.9	29.2
RH - %	-1.0	66.5	59.8	54.1	51.6	48.7	47.7	48.8	58.5	57.0	65.0	75.8
O3 - PPM	-1.000	.062	.110	.100	.105	.116	.118	.102	.073	.078	.065	.048
NO - PPM	-1.000	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005
NOX - PPM	-1.000	.034	.005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	.008	.005	.008	.006	.006	.006	.006	.005	.003	.005	.003	.003
FREON 11 -PPT	245.	250.	223.	160.	217.	135.	300.	273.	179.	-1.	-1.	-1.
CO - PPM	-1.00	.75	2.21	.48	.45	.50	.82	.53	.48	.53	.74	.57

	22	23	24	1	2	3	4	5	6	7	8	9
IRAD - LANGLEY/M	.019	.017	.016	.014	.015	.013	.014	.013	.012	.018	.146	.316
WIND SPEED - MPH	3.13	2.60	3.83	4.67	3.63	2.53	3.00	2.83	3.20	2.37	4.07	4.80
WIND DIR - DEG	117.	139.	160.	167.	176.	194.	185.	127.	135.	114.	173.	192.
TEMP - DEG C	27.6	27.2	27.3	26.9	26.8	25.8	25.6	24.5	23.9	24.1	27.6	28.7
RH - %	80.6	81.2	82.3	84.2	83.8	86.8	87.1	90.7	93.2	93.8	85.6	80.2
O3 - PPM	.035	.036	.029	.020	.007	.012	.010	.006	.015	.011	.024	.052
NO - PPM	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005
NOX - PPM	≤ .005	≤ .005	≤ .005	.006	.020	.010	.012	.012	≤ .005	≤ .005	.021	.028
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	.003	.003	.003	.002	.002	≤ .001	.002	≤ .001	≤ .001	≤ .001	.003	.006
FREON 11 -PPT	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.
CO - PPM	.51	.40	.49	.55	.83	.56	.52	.52	.36	.46	.79	1.05

DAILY AVERAGE

IRAD - LANGLEY/M	.264
WIND SPEED - MPH	4.65
WIND DIR - DEG	170.
TEMP - DEG C	30.0
RH - %	72.3
O3 - PPM	.054
NO - PPM	≤ .005
NOX - PPM	.008
HNO3 - PPM	≤ .006
PAN - PPM	.004
FREON 11 -PPT	220.
CO - PPM	.66

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                             BETHALTO, ILL.

                             JULY   19, 1977


                      10        11        12        13        14        15        16        17        18        19        20        21
IRAD - LANGLEY/M     .490      .636      .763      .759      .799      .620      .580      .455      .208      .121      .074      .028
WIND SPEED - MPH    6.47      7.63      8.07      7.30      6.90      6.77      7.10      6.33      7.10      5.97      6.47      2.73
WIND DIR - DEG    190.      209.      195.      199.      163.      149.      160.      156.      168.      165.      162.      155.
TEMP - DEG C       30.3      31.8      34.5      35.8      38.5      39.4      39.4      38.5      34.6      32.9      31.6      29.7
RH - %             74.8      68.4      60.1      55.9      50.7      48.9      49.1      49.0      58.6      63.6      67.7      74.6
O3 - PPM              .111      .146      .141      .137      .111      .107      .102      .102      .090      .077      .063      .055
NO - PPM          ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005
NOX - PPM             .020      .007  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005
HNO3 - PPM        ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006
PAN - PPM             .012      .014      .012      .008      .005      .002      .003      .002      .003      .002      .003      .003
FREON 11 -PPT     299.      438.      492.      330.      268.      220.      159.      220.      180.      203.      627.      223.
CO - PPM             1.17      1.11       .96       .72       .47       .38       .40       .45       .48       .59       .55       .53


                      22        23        24         1         2         3         4         5         6         7         8         9
IRAD - LANGLEY/M     .016      .015      .014      .014      .014      .013      .013      .012      .013      .020      .021      .147
WIND SPEED - MPH    4.57      3.23      2.73      1.13      1.97      3.23      2.87      3.57      2.13      2.50      3.67      3.60
WIND DIR - DEG    127.      136.      153.      141.      138.       82.       86.      120.      105.       82.      109.      102.
TEMP - DEG C       27.8      26.7      25.9      25.4      25.0      23.8      23.6      23.5      23.2      23.5      24.9      26.9
RH - %             80.0      83.4      86.3      88.3      89.8      93.7      95.3      95.2      96.4      95.9      93.2      88.4
O3 - PPM              .045      .040      .034      .029      .023      .015      .009      .011      .012      .016      .015      .021
NO - PPM          ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005
NOX - PPM         ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005
HNO3 - PPM        ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006
PAN - PPM             .003      .003      .002     -.002     -.002     -.002     -.002     -.002      .002      .002      .002      .002
FREON 11 -PPT     211.      175.      149.      174.      320.      178.      234.       -1.       -1.       -1.       -1.       -1.
CO - PPM              .51       .37       .33       .36       .40       .32       .32       .28       .25       .63       .41       .33


      DAILY AVERAGE

IRAD - LANGLEY/M     .243
WIND SPEED - MPH    4.75
WIND DIR - DEG    144.
TEMP - DEG C       29.9
RH - %             75.3
O3 - PPM              .063
NO - PPM          ≤   .005
NOX - PPM         ≤   .005
HNO3 - PPM        ≤   .006
PAN - PPM             .004
FREON 11 -PPT     268.
CO - PPM              .51
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                        BETHALTO, ILL.

                        JULY   20, 1977


                        10          11          12          13          14          15          16          17          18          19          20          21
IRAD - LANGLEY/M       .209        .276        .606        .580        .675        .795        .557        .347        .284        .219        .044        .022
WIND SPEED - MPH      3.57        6.13        6.37        5.23        5.73        8.33        7.50        6.13        7.77        5.50        3.00        4.97
WIND DIR - DEG      141.        160.        139.        146.        130.        140.        148.        157.        150.        152.        146.        161.
TEMP - DEG C         28.1        29.3        31.8        32.9        34.7        36.0        35.4        33.8        33.3        33.0        29.5        28.1
RH - %               83.0        76.4        69.7        65.9        60.1        56.2        57.1        59.4        61.9        62.3        69.5        75.2
O3 - PPM               .028        .035        .042        .050        .055        .053        .056        .056        .059        .057        .049        .040
NO - PPM            ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005
NOX - PPM           ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005        .007        .013
HNO3 - PPM          ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006
PAN - PPM              .002        .002        .002        .002     ≤  .001        .002        .002        .002        .002        .002        .002     ≤  .001
FREON 11 -PPT       546.        248.        172.        263.        323.        314.        437.        392.        397.        246.        340.        175.
CO - PPM               .29         .29         .45         .36         .66         .23         .21         .20         .28        -.31         .33         .40


                        22          23          24           1           2           3           4           5           6           7           8           9
IRAD - LANGLEY/M       .018        .015        .013        .014        .013        .013        .013        .013        .013        .018        .110        .128
WIND SPEED - MPH      2.93        4.30        4.77        5.70        1.93        2.63        3.30        2.90        3.07        3.73        4.17        3.68
WIND DIR - DEG      177.        149.        165.        163.        122.        155.        174.        166.        170.        188.        186.        226.
TEMP - DEG C         27.5        27.3        26.2        25.7        24.6        24.7        24.5        24.1        23.8        24.1        26.0        25.8
RH - %               77.8        80.3        83.9        86.1        90.4        90.9        92.5        94.6        96.4        97.5        92.1        91.5
O3 - PPM               .031        .028        .030        .027        .024        .023        .020        .013        .011        .004        .017        .018
NO - PPM            ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005        .007
NOX - PPM              .018        .009     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005     ≤  .005        .009        .030        .034
HNO3 - PPM          ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006     ≤  .006
PAN - PPM              .002        .002     ≤  .001     ≤  .001     ≤  .001     ≤  .001     ≤  .001     ≤  .001     ≤  .001     ≤  .001        .002        .002
FREON 11 -PPT       238.        356.        234.        209.        249.        519.        395.        220.        221.        198.        208.        214.
CO - PPM               .58         .43         .33         .35         .28         .34         .25         .31         .29         .31         .60         .77


       DAILY AVERAGE

IRAD - LANGLEY/M       .208
WIND SPEED - MPH      4.72
WIND DIR - DEG      159.
TEMP - DEG C         28.8
RH - %               77.9
O3 - PPM               .034
NO - PPM            ≤  .005
NOX - PPM              .006
HNO3 - PPM          ≤  .006
PAN - PPM           ≤  .001
FREON 11 -PPT       296.
CO - PPM               .37
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BETHALTO, ILL.

JULY 21, 1977

	10	11	12	13	14	15	16	17	18	19	20	21
IRAD - LANGLEY/M	.383	.611	.269	.222	.806	.607	.446	.201	.064	.065	.034	.020
WIND SPEED - MPH	2.43	2.10	2.53	3.80	4.67	5.73	1.27	0.00	0.00	0.00	0.00	0.00
WIND DIR - DEG	196.	196.	166.	116.	154.	127.	130.	164.	-1.	-1.	-1.	-1.
TEMP - DEG C	28.1	31.6	30.1	30.5	34.8	35.7	35.2	32.6	27.3	25.7	25.1	24.6
RH - %	83.6	72.1	75.4	73.9	66.6	62.0	58.0	62.9	83.1	91.3	94.6	101.0
O3 - PPM	.016	.039	.045	.068	.094	.116	.104	.093	.075	.061	.046	.036
NO - PPM	.010	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005
NOX - PPM	.038	.027	.017	.013	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	.002	.002	.002	.003	.006	.008	.006	.005	.003	.002	.002	.002
FREON 11 -PPT	329.	305.	241.	204.	252.	402.	410.	220.	200.	223.	137.	143.
CO - PPM	.34	.47	.48	.53	.51	.56	1.03	.56	.46	.40	3.03	.30

	22	23	24	1	2	3	4	5	6	7	8	9
IRAD - LANGLEY/M	.016	.015	.014	.014	.013	.013	.012	.011	.013	.021	.041	.147
WIND SPEED - MPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	-1.00
WIND DIR - DEG	67.	5.	9.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.
TEMP - DEG C	24.2	23.9	23.7	23.4	23.3	23.2	22.4	21.5	21.1	20.9	21.4	22.2
RH - %	101.2	102.9	102.8	102.9	102.9	102.8	102.9	102.8	102.8	102.9	102.9	100.4
O3 - PPM	.029	.025	.028	.033	.035	.041	.039	.032	.025	.020	.018	.028
NO - PPM	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005
NOX - PPM	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001
FREON 11 -PPT	150.	126.	118.	132.	140.	142.	142.	135.	139.	140.	145.	134.
CO - PPM	.41	.36	.24	.20	.22	.30	.35	.30	.33	.33	.39	.34

DAILY AVERAGE

IRAD - LANGLEY/M	.169
WIND SPEED - MPH	1.02
WIND DIR - DEG	121.
TEMP - DEG C	26.4
RH - %	69.8
O3 - PPM	.047
NO - PPM	≤ .005
NOX - PPM	≤ .005
HNO3 - PPM	≤ .006
PAN - PPM	.002
FREON 11 -PPT	196.
CO - PPM	.52

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                                 BETHALTO, ILL.

                                 JULY   22, 1977

                      10       11       12       13       14       15       16       17       18       19       20       21
IRAD - LANGLEY/M    -.166     .184     .231     .356     .378     .585     .699     .531     .440     .264     .106     .024
WIND SPEED - MPH   -1.00    -1.00    -1.00    -1.00    -1.00    -1.00     7.08     8.17     9.37     7.93     5.93     5.77
WIND DIR - DEG     -1.      -1.      -1.      -1.      -1.      -1.      -1.      71.      64.      61.      57.      38.
TEMP - DEG C      -23.2     24.1     24.8     26.8     28.7     29.0     30.3     30.5     30.2    -29.0     27.8     23.9
RH - %            -97.4     94.4     92.3     84.8     79.7     72.4     61.6     57.8     57.4     55.1     57.1     70.0
O3 - PPM            -.022     .024     .023     .037     .049     .051     .064     .077   . .073     .070     .055     .016
NO - PPM          ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005
NOX - PPM         ≤  .005  ≤  .005     .015     .007     .007     .011     .006  ≤  .005  ≤  .005  ≤  .005  ≤  .005     .007
HNO3 - PPM        ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006
PAN - PPM         ≤  .001  ≤  .001  ≤  .001     .002     .002     .002     .002     .002     .002     .002  ≤  .001  ≤  .001
FREON 11 -PPT     144.     144.     138.     146.     130.     132.     174.     117.     132.     142.     126.     152.
CO - PPM            -.51      .69      .27      .86      .51     1.79      .81     1.57     1.22      .75      .30      .82


                      22       23       24        1        2        3        4        5        6        7        8        9
IRAD - LANGLEY/M     .016     .015     .013     .013     .012     .012     .012     .011     .012     .020     .164     .356
WIND SPEED - MPH    4.17     4.07     3.23     3.73     2.70     2.30     3.07     3.77     3.27     3.70     3.97     6.83
WIND DIR - DEG     44.      52.      69.      83.      63.      59.      61.      73.     104.      76.      84.     113.
TEMP - DEG C       22.2     21.3     20.3     19.9     19.5     19.1     18.7     18.1     18.0     18.5     22.3     24.5
RH - %             76.5     79.0     81.9     81.7     82.3     83.2     84.9     87.4     88.5     87.9     79.6     69.4
O3 - PPM             .028     .030     .028     .029     .032     .031     .028     .027     .021     .020     .021     .032
NO - PPM          ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005
NOX - PPM            .008     .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005  ≤  .005     .006  ≤  .005
HNO3 - PPM        ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006  ≤  .006
PAN - PPM         ≤  .001  ≤  .001  ≤  .001  ≤  .001  ≤  .001  ≤  .001  ≤  .001  ≤  .001  ≤  .001  ≤  .001  ≤  .001  ≤  .001
FREON 11 -PPT     161.     160.     146.     150.     162.     178.     147.     136.     160.     204.     228.     270.
CO - PPM             .73      .36      .60    -1.00    -1.00    -1.00    -1.00    -1.00    -1.00    -1.00    -1.00    -1.00


        DAILY AVERAGE

IRAD - LANGLEY/M     .192
WIND SPEED - MPH    4.95
WIND DIR - DEG     69.
TEMP - DEG C       24.3
RH - %             77.6
O3 - PPM             .038
NO - PPM          ≤  .005
NOX - PPM         ≤  .005
HNO3 - PPM        ≤  .006
PAN - PPM         ≤  .001
FREON 11 -PPT     157.
CO - PPM             .79
```

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                    BETHALTO, ILL.

                    JULY   25, 1977


                          10        11        12        13        14        15        16        17        18        19        20        21
IRAD - LANGLEY/M        .231      .432      .294      .319      .571      .585      .753      .252      .239      .200      .088      .023
WIND SPEED - MPH        5.26      6.17      4.87      3.97      5.37      6.97      7.70     -1.00     -1.00     -1.00     -1.00     -1.00
WIND DIR - DEG          211.      312.      270.      231.      275.      315.       76.       -1.       -1.       -1.       -1.       -1.
TEMP - DEG C            24.8      28.0      29.3      29.4      29.9      30.3      25.7      -1.0      -1.0      -1.0      -1.0      -1.0
RH - %                  97.8      97.6      91.3      90.9      87.1      79.1      58.3      -1.0      -1.0      -1.0      -1.0      -1.0
O3 - PPM                .047      .054      .064      .055      .059      .060      .066      .066      .069      .075      .080      .069
NO - PPM              ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005
NOX - PPM               .013      .008      .007      .011      .007      .007    ≤ .005      .007      .005      .008      .007      .009
HNO3 - PPM            ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006
PAN - PPM             ≤ .001      .002      .002    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001
FREON 11 -PPT           143.      180.      165.      173.      140.      147.     -148.     -149.      150.      155.      158.     -179.
CO - PPM                 .31       .20       .26      -.30       .34       .31       .21      1.13       .28       .49       .34       .40
                                                                                                                                  .62
                                                                                                                                  .49


                          22        23        24         1         2         3         4         5         6         7         8         9
IRAD - LANGLEY/M        .016      .015      .013      .012      .012      .011      .012      .010      .011      .025      .233      .434
WIND SPEED - MPH       -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00
WIND DIR - DEG           -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.
TEMP - DEG C            -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0
RH - %                  -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0
O3 - PPM                .063      .063      .050      .036      .028      .025      .023      .018      .015      .015      .018      .022
NO - PPM              ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005    ≤ .005
NOX - PPM               .009      .005    ≤ .005      .005    ≤ .005    ≤ .005    ≤ .005      .006      .007      .007      .008      .011
HNO3 - PPM            ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006    ≤ .006
PAN - PPM             ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001    ≤ .001
FREON 11 -PPT           214.      174.      170.      147.      139.      133.      127.      128.      132.      144.      144.      130.
CO - PPM                 .35       .27       .25       .20       .18       .17       .17       .17       .17       .26       .35       .51
                                                                                1.62      1.63      1.62      1.63      1.62      1.63
                                                                                1.17      1.23      1.33      1.20      5.13      2.80

        DAILY AVERAGE

IRAD - LANGLEY/M        .200
WIND SPEED - MPH        5.76
WIND DIR - DEG          241.
TEMP - DEG C            28.2
RH - %                  66.0
O3 - PPM                .047
NO - PPM              ≤ .005
NOX - PPM               .007
HNO3 - PPM            ≤ .006
PAN - PPM             ≤ .001
FREON 11 -PPT           153.
CO - PPM                 .32
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                              BETHALTO, ILL.

                              JULY   26, 1977


                      10        11        12        13        14        15        16        17        18        19        20        21
IRAD - LANGLEY/M     .600      .400      .840      .874      .897      .850      .751      .651      .483      .304      .119      .022
O3 - PPM             .019      .027      .028      .037      .041      .042      .043      .043      .050      .048      .043      .026
NO - PPM          ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005
NOX - PPM         ≤  .005   ≤  .005      .012   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005      .007
HNO3 - PPM        ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
PAN - PPM         ≤  .001   ≤  .001   ≤  .001   ≤  .001      .002      .002      .002      .002      .002   ≤  .001   ≤  .001      .002
FREON 11 -PPT     122.      126.      116.      114.      140.      140.      120.     -144.     -168.     -192.     -216.      240.
CO - PPM             .17       .29       .28       .36       .40       .15       .59       .51       .26       .98       .35       .50


                      22        23        24         1         2         3         4         5         6         7         8         9
IRAD - LANGLEY/M     .015      .013      .012      .012      .012      .012      .011      .010      .011      .018      .092      .315
O3 - PPM             .015      .020      .021      .022      .029      .026      .022      .013      .014      .012      .009      .013
NO - PPM          ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005
NOX - PPM            .009   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005      .006   ≤  .005
HNO3 - PPM        ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
PAN - PPM         ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001      .002      .002
FREON 11 -PPT     235.      158.      128.      139.      172.     -171.     -170.     -169.     -168.      167.      160.      150.
CO - PPM             .36      -.30       .25       .23       .18       .16       .15       .15       .16       .22       .47       .30


      DAILY AVERAGE

IRAD - LANGLEY/M     .305
O3 - PPM             .028
NO - PPM          ≤  .005
NOX - PPM         ≤  .005
HNO3 - PPM        ≤  .006
PAN - PPM         ≤  .001
FREON 11 -PPT     159.
CO - PPM             .32
```

BETHALTO, ILL.

JULY 27, 1977

	10	11	12	13	14	15	16	17	18	19	20	21
IRAD - LANGLEY/M	.419	.730	.808	.885	.904	.825	.669	.621	.452	.277	.105	.022
O3 - PPM	.016	.032	.053	.066	.074	.076	.081	.078	.086	.078	.069	.062
NO - PPM	.007	.005	.008	.007	.006	.005	.005	.006	≤ .005	≤ .005	≤ .005	≤ .005
NOX - PPM	.011	.011	.011	.011	.010	.009	.007	.009	.006	.007	.008	.009
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	.002	.002	.002	.002	.002	.002	.003	.003	.003	.003	.002	.002
FREON 11 -PPT	161.	217.	209.	351.	364.	150.	170.	209.	232.	309.	376.	505.
CO - PPM	.96	.52	.38	.81	.44	.49	.22	.50	.52	.34	.60	.36

	22	23	24	1	2	3	4	5	6	7	8	9
IRAD - LANGLEY/M	.015	.014	.012	.012	.012	.011	.011	.011	.011	.025	.189	.371
O3 - PPM	.059	.056	.033	.020	.005	.018	.016	.005	.015	.013	.010	.030
NO - PPM	≤ .005	≤ .005	≤ .005	≤ .005	.011	≤ .005	≤ .005	≤ .005	≤ .005	.020	.012	≤ .005
NOX - PPM	.009	.009	.014	.022	.039	.017	.015	.021	.011	.035	.027	.016
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	.002	.002	.002	.002	.002	≤ .001	.002	.002	≤ .001	≤ .001	≤ .001	≤ .001
FREON 11 -PPT	1065.	1069.	218.	278.	276.	-295.	-314.	-332.	-351.	370.	314.	290.
CO - PPM	.50	.26	.31	.59	.71	.43	.37	.45	.30	.50	.79	.53

DAILY AVERAGE

IRAD - LANGLEY/M	.309
O3 - PPM	.044
NO - PPM	.005
NOX - PPM	.014
HNO3 - PPM	≤ .006
PAN - PPM	.001
FREON 11 -PPT	353.
CO - PPM	.50

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                         BETHALTO, ILL.

                         JULY   28, 1977


                     10        11        12        13        14        15        16        17        18        19        20        21
IRAD - LANGLEY/M    .555      .673      .766      .798      .805      .702      .457      .538      .367      .199      .081      .023
O3 - PPM            .055      .087      .106      .107      .129      .153      .137      .126      .122      .113      .092      .073
NO - PPM            .006      .005      .005      .005      .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005
NOX - PPM           .016      .016      .015      .015      .017      .014      .017      .011      .014      .011      .011      .013
HNO3 - PPM       ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
PAN - PPM           .002      .003      .003      .003      .005      .008      .006      .006      .005      .003      .003      .002
FREON 11 -PPT    290.      213.      257.      254.      463.      427.      192.      221.      197.      201.      261.      265.
CO - PPM            .35       .31       .37       .53       .82       .50       .55       .58       .63       .45       .37       .52


                     22        23        24         1         2         3         4         5         6         7         8         9
IRAD - LANGLEY/M    .016      .014      .014      .013      .012      .014      .011      .012      .012      .015      .026      .155
O3 - PPM            .067      .059      .045      .028      .036      .025      .019      .012      .008      .003      .005      .017
NO - PPM         ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005      .010      .025      .015
NOX - PPM           .014      .015      .019      .032      .023      .031      .028      .038      .036      .038      .063      .053
HNO3 - PPM       ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
PAN - PPM           .002      .002      .002      .002      .002      .002      .002      .002      .002      .002      .002      .002
FREON 11 -PPT    436.      359.      250.        -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.      304.
CO - PPM            .44       .58       .53       .67       .56       .71       .68       .71       .70      1.10      1.23      1.35


        DAILY AVERAGE

IRAD - LANGLEY/M     .262
O3 - PPM             .068
NO - PPM          ≤  .005
NOX - PPM            .023
HNO3 - PPM        ≤  .006
PAN - PPM            .003
FREON 11 -PPT     287.
CO - PPM             .63
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                          BETHALTO, ILL.

                          JULY   29, 1977


                      10        11        12        13        14        15        16        17        18        19        20        21
IRAD - LANGLEY/M     .388      .630      .787      .702      .827      .740      .622      .521      .427      .261      .098      .023
O3 - PPM             .033      .062      .058      .049      .056      .060      .061      .066      .059      .054      .034      .010
NO - PPM             .009  ≤   .005  ≤   .005      .008      .006  ≤   .005  ≤   .005  ≤   .005      .006  ≤   .005  ≤   .005      .015
NOX - PPM            .029      .007      .009      .028      .017      .012      .007      .009      .011      .007      .018      .048
HNO3 - PPM       ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006
PAN - PPM            .002      .002      .002      .002      .002  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001      .002      .002
FREON 11 -PPT    300.      124.      146.      142.      147.      176.      130.      140.      117.      184.      184.      234.
CO - PPM              .94       .40       .35       .39       .27       .26       .26       .25       .25       .31       .49      1.50


                      22        23        24         1         2         3         4         5         6         7         8         9
IRAD - LANGLEY/M     .018      .013      .014      .014      .012      .012      .010      .011      .012      .021      .180      .349
O3 - PPM             .003  ≤   .002  ≤   .002  ≤   .002  ≤   .002  ≤   .002  ≤   .002  ≤   .002  ≤   .002  ≤   .002      .056      .146
NO - PPM             .023      .011      .048      .012      .062      .047      .012      .010      .016      .027      .012  ≤   .005
NOX - PPM            .058      .034      .077      .053      .100      .070      .030      .031      .035      .044      .051      .031
HNO3 - PPM       ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006
PAN - PPM            .002      .003      .002      .002  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001      .014      .023
FREON 11 -PPT    353.      338.      430.      800.      520.      465.      229.      230.     -320.     -410.     -500.      590.
CO - PPM             1.99      1.09       .70       .67       .62       .57       .53       .48       .43       .38       .33       .28


      DAILY AVERAGE

IRAD - LANGLEY/M     .279
O3 - PPM             .034
NO - PPM             .015
NOX - PPM            .034
HNO3 - PPM       ≤   .006
PAN - PPM            .002
FREON 11 -PPT    300.
CO - PPM              .57
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                      BETHALTO, ILL.

                      JULY   30, 1977

                      10        11        12        13        14        15        16        17        18        19        20        21
IRAD - LANGLEY/M     .543      .678      .758      .810      .833      .796      .670      .524      .304      .166      .100      .023
WIND SPEED - MPH   -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00      8.17      6.93      6.27
WIND DIR - DEG     -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.       -1.      166.
TEMP - DEG C       -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      27.9
RH - %             -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      -1.0      66.0
O3 - PPM             .149      .138      .121      .099      .081      .085      .102      .082      .075      .062      .061      .056
NO - PPM             .006      .005      .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005
NOX - PPM            .027      .017      .006      .012      .012      .008      .008      .006      .008  ≤   .005  ≤   .005      .007
HNO3 - PPM       ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006
PAN - PPM            .018      .014      .014      .006      .003      .002      .002      .002      .002      .002      .002  ≤   .001
FREON 11 -PPT      390.      234.      220.      242.      253.      231.      193.      212.      208.      230.      240.      176.
CO - PPM             .62       .56       .50       .60       .39       .22       .23       .30      1.28       .25       .25       .28


                      22        23        24         1         2         3         4         5         6         7         8         9
IRAD - LANGLEY/M     .015      .015      .014      .013      .013      .012      .012      .014      .009      .020      .045      .220
WIND SPEED - MPH    8.27      9.10     11.20      9.87      7.47      6.90      4.40      9.03     12.47     10.13     11.23      7.16
WIND DIR - DEG    175.      167.      178.      186.      182.      183.      171.       92.      108.      117.      128.      134.
TEMP - DEG C        26.3      25.4      25.0      24.6      24.5      23.6      23.3      22.2      18.6      18.8      18.9      20.3
RH - %              70.6      75.8      78.1      80.3      82.3      85.9      88.0      88.8      86.1      81.9      66.3      66.8
O3 - PPM             .036      .032      .035      .027      .005  ≤   .002      .006      .015      .044      .040      .040      .040
NO - PPM         ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005  ≤   .005
NOX - PPM            .015      .012      .006      .011      .033      .036      .029      .021  ≤   .005  ≤   .005  ≤   .005  ≤   .005
HNO3 - PPM       ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006  ≤   .006
PAN - PPM        ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001  ≤   .001
FREON 11 -PPT      143.      170.      216.      186.      206.      176.      180.      150.     -163.     -176.     -189.      202.
CO - PPM             .26       .29       .25       .29       .65       .72       .67       .48       .11       .10       .13       .16


       DAILY AVERAGE

IRAD - LANGLEY/M        .275
WIND SPEED - MPH       8.57
WIND DIR - DEG       153.
TEMP - DEG C          23.8
RH - %                78.2
O3 - PPM                .060
NO - PPM          ≤     .005
NOX - PPM               .012
HNO3 - PPM        ≤     .006
PAN - PPM               .003
FREON 11 -PPT    [illegible]
CO - PPM                .43
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                              BETHALTO, ILL.

                              AUGUST  1, 1977


                      10         11         12         13         14         15         16         17         18         19         20         21
IRAD - LANGLEY/M     .583       .711       .820       .862       .826       .825       .661       .588       .444       .269       .091       .020
WIND SPEED - MPH    5.43       6.13       7.20       9.03       9.80      10.83       9.40       7.20       5.40       4.67       3.37       4.50
WIND DIR - DEG    190.       160.       231.       336.       171.       181.       228.       179.       62.        99.        128.       130.

RH - %              38.4       44.4       49.4       40.4       48.6       47.6       47.4       47.7       47.8       47.7       50.0       49.8
O3 - PPM              .024       .029       .032       .033       .037       .037       .037       .036       .043       .044       .037       .031
NO - PPM          ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005
NOX - PPM         ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005       .006       .005       .006
HNO3 - PPM        ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006
PAN - PPM         ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001
FREON 11 -PPT     216.       214.       147.       158.       167.       191.       239.      -213.      -186.       160.       160.       160.
CO - PPM             .13        .16        .25        .14        .13        .14        .41        .17        .14        .22        .49        .45



                      22         23         24          1          2          3          4          5          6          7          8          9
IRAD - LANGLEY/M     .015       .013       .011       .012       .012       .011       .011       .011       .010       .028       .188       .238
WIND SPEED - MPH    2.97       2.53       4.23       1.33       1.40       3.13       2.93       2.20       3.27       2.17       3.37       5.84
WIND DIR - DEG    151.       146.       138.       197.       152.       135.       140.       107.       142.       139.       229.       206.

RH - %              56.3       54.8       45.7       60.9       66.2       58.0       56.9       68.9       72.8       74.4       49.6       75.2
O3 - PPM              .016       .016       .010       .005       .039       .006       .012       .007       .008       .002       .015       .025
NO - PPM          ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005   ≤   .005       .014       .011
NOX - PPM             .012       .017       .017       .021       .017       .021       .017       .015       .014       .016       .044       .054
HNO3 - PPM        ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006   ≤   .006
PAN - PPM         ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001   ≤   .001       .002       .002
FREON 11 -PPT     150.       200.       282.       280.       316.       316.       310.       248.       216.       294.       283.       280.
CO - PPM             .33        .37        .26        .41        .40        .33        .30        .28        .25        .36        .81       1.14


     DAILY AVERAGE

IRAD - LANGLEY/M     .303
WIND SPEED - MPH    4.93
WIND DIR - DEG    166.

RH - %              54.1
O3 - PPM              .024
NO - PPM          ≤   .005
NOX - PPM             .013
HNO3 - PPM        ≤   .006
PAN - PPM         ≤   .001
FREON 11 -PPT     224.
CO - PPM             .34
```

BETHALTO, ILL.

AUGUST 2, 1977

	10	11	12	13	14	15	16	17	18	19	20	21
IRAD - LANGLEY/M	.243	.156	.235	.258	.280	.315	.190	.181	.344	.259	.086	.020
WIND SPEED - MPH	5.07	5.33	6.90	7.30	4.10	3.07	3.33	4.47	7.07	7.03	3.80	1.93
WIND DIR - DEG	219.	197.	170.	180.	159.	153.	197.	195.	174.	185.	169.	166.
TEMP - DEG C	20.9	21.6	23.4	24.7	25.2	26.9	24.7	24.4	27.5	27.3	25.6	22.1
RH - %	47.1	70.6	66.7	63.8	63.1	59.8	61.6	63.9	60.1	57.9	60.4	68.6
O3 - PPM	.038	.025	.033	.049	.057	.077	.061	.060	.079	.080	.062	.052
NO - PPM	.009	.009	.010	.008	.005	.005	≤ .005	.006	.006	≤ .005	≤ .005	≤ .005
NOX - PPM	.055	.055	.050	.044	.030	.024	.033	.038	.023	.023	.028	.024
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	.002	.003	.003	.003	.003	.005	.005	.005	.003	.003	.003	.003
FREON 11 -PPT	251.	213.	255.	254.	241.	384.	384.	-384.	-345.	-306.	-267.	228.
CO - PPM	.75	.74	.92	1.00	.68	.48	.76	1.23	.68	.46	.58	.52

	22	23	24	1	2	3	4	5	6	7	8	9
IRAD - LANGLEY/M	.016	.015	.012	.013	.012	.012	.012	.012	.011	.020	.152	.385
WIND SPEED - MPH	3.00	5.37	4.40	8.63	6.87	6.50	9.27	7.23	5.63	4.27	5.80	7.08
WIND DIR - DEG	184.	174.	162.	177.	189.	197.	206.	211.	208.	216.	245.	289.
TEMP - DEG C	20.8	21.0	19.7	19.9	19.8	19.0	19.8	19.3	18.5	18.3	19.5	20.8
RH - %	71.7	61.4	50.5	50.5	45.3	67.0	56.4	51.7	47.2	51.3	49.6	43.1
O3 - PPM	.030	.032	.019	.030	.005	.023	.026	.014	.011	.022	.034	.028
NO - PPM	.006	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	.005	.007	.007	.010
NOX - PPM	.035	.019	.014	.016	.034	.028	.034	.032	.030	.035	.030	.035
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	.002	.002	.002	.002	.002	.002	≤ .001	.002	.002	.003	.003	.002
FREON 11 -PPT	246.	258.	200.	191.	240.	247.	176.	186.	207.	230.	226.	185.
CO - PPM	.84	.55	.34	.33	.41	.32	.38	.33	.28	.33	.29	.27

DAILY AVERAGE

IRAD - LANGLEY/M	.135
WIND SPEED - MPH	5.56
WIND DIR - DEG	193.
TEMP - DEG C	22.1
RH - %	57.9
O3 - PPM	.039
NO - PPM	.006
NOX - PPM	.032
HNO3 - PPM	≤ .006
PAN - PPM	.002
FREON 11 -PPT	254.
CO - PPM	.56

BETHALTO, ILL.

AUGUST 3, 1977

	10	11	12	13	14	15	16	17	18	19	20	21
IRAD - LANGLEY/M	.511	.407	.851	.850	.825	.777	.701	.469	.402	.236	.085	.022
WIND SPEED - MPH	5.70	3.97	4.77	4.87	4.87	5.03	5.47	3.73	3.90	3.63	2.90	5.37
WIND DIR - DEG	314.	322.	161.	310.	279.	285.	302.	147.	174.	180.	159.	173.
TEMP - DEG C	12.0	7.7	12.2	13.5	15.6	17.9	19.2	20.6	19.5	17.9	14.7	14.4
RH - %	59.7	71.6	63.8	58.4	54.3	50.0	46.2	47.8	48.2	48.3	51.3	59.0
O3 - PPM	.061	.061	.064	.065	.067	.068	.076	.104	.113	.113	.100	.036
NO - PPM	≤ .005	≤ .005	.007	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005
NOX - PPM	.013	.008	.006	.006	.005	.006	.006	.012	.012	.013	.011	.012
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	≤ .001	≤ .001	≤ .001	≤ .001
FREON 11 -PPT	236.	199.	150.	270.	235.	170.	199.	198.	155.	211.	377.	213.
CO - PPM	.19	.16	.15	.13	.15	.18	.17	.30	.26	.28	.30	.42

	22	23	24	1	2	3	4	5	6	7	8	9
IRAD - LANGLEY/M	.015	.014	.012	.013	.011	.010	.012	.011	.011	.025	.057	.156
WIND SPEED - MPH	4.90	2.67	2.63	4.40	2.80	1.30	1.83	2.87	3.03	5.87	6.90	6.52
WIND DIR - DEG	176.	178.	121.	177.	111.	139.	141.	139.	132.	193.	198.	176.
TEMP - DEG C	23.6	22.3	21.2	21.4	18.3	17.3	17.1	16.7	16.5	18.6	19.4	18.9
RH - %	65.7	70.7	78.6	73.2	54.5	58.5	45.5	57.8	81.0	51.4	54.5	33.6
O3 - PPM	.081	.059	.048	.033	.024	.027	.015	.027	.024	.008	.005	.005
NO - PPM	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	≤ .005	.007	.028	.034
NOX - PPM	.015	.021	.020	.024	.017	.015	.020	.008	.007	.028	.066	.091
HNO3 - PPM	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006	≤ .006
PAN - PPM	.002	.002	-.002	.002	.002	.002	.002	.003	.005	.003	-1.000	-1.000
FREON 11 -PPT	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	455.	217.	176.	212.
CO - PPM	.56	.51	.47	.58	.49	.45	.47	.99	.36	.52	.78	1.09

DAILY AVERAGE

IRAD - LANGLEY/M	.270
WIND SPEED - MPH	4.16
WIND DIR - DEG	196.
TEMP - DEG C	17.4
RH - %	57.6
O3 - PPM	.056
NO - PPM	.006
NOX - PPM	.018
HNO3 - PPM	≤ .006
PAN - PPM	.002
FREON 11 -PPT	230.
CO - PPM	.41

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                                        BETHALTO, ILL.

                                 1977 FIELD PROGRAM AVERAGES


                     10        11        12        13        14        15        16        17        18        19        20        21
IRAD - LANGLEY/M     .426      .532      .644      .687      .722      .657      .571      .457      .337      .223      .093      .025
WIND SPEED - MPH    4.83      5.60      5.45      5.97      5.90      6.26      5.59      5.66      5.72      5.50      4.40      3.87
WIND DIR - DEG     195.      217.      207.      197.      184.      170.      168.      149.      148.      163.      142.      153.
TEMP - DEG C        25.2      26.9      28.6      29.6      31.7      32.6      32.1      32.2      30.7      30.9      28.1      26.6
RH - %              76.0      74.4      70.4      66.6      63.4      60.0      58.1      59.1      61.8      63.2      67.9      73.3
O3 - PPM             .054      .064      .074      .077      .081      .086      .084      .081      .077      .075      .063      .051
NO - PPM          ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005
NOX - PPM            .018      .017      .013      .010      .008      .006      .006      .006      .007      .007      .009      .011
HNO3 - PPM        ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
PAN - PPM            .004      .005      .005      .003      .003      .003      .003      .002      .002      .001      .001      .001
FREON 11 -PPT      301.      262.      275.      271.      249.      242.      232.      227.      210.      209.      235.      215.
CO - PPM              .95      1.00      1.10       .98       .86       .69       .59       .63       .54       .50       .65       .58



                     22        23        24         1         2         3         4         5         6         7         8         9
IRAD - LANGLEY/M     .016      .015      .014      .014      .013      .013      .013      .012      .012      .024      .132      .292
WIND SPEED - MPH    3.48      3.71      3.87      4.24      3.65      3.38      3.38      3.77      3.54      3.50      4.51      4.58
WIND DIR - DEG     142.      143.      141.      166.      157.      154.      153.      137.      140.      143.      168.      181.
TEMP - DEG C        26.4      25.8      25.1      24.7      24.1      23.3      22.8      22.0      21.2      21.6      23.6      25.1
RH - %              78.3      80.0      81.1      83.2      83.5      86.8      87.0      88.3      90.7      88.5      82.3      77.4
O3 - PPM             .038      .033      .028      .021      .019      .018      .016      .015      .015      .014      .022      .036
NO - PPM          ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005   ≤  .005      .005      .005   ≤  .005
NOX - PPM            .014      .012      .014      .017      .022      .018      .017      .015      .013      .016      .021      .021
HNO3 - PPM        ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006   ≤  .006
PAN - PPM         ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001   ≤  .001      .002      .003
FREON 11 -PPT      276.      294.      227.      245.      249.      255.      232.      217.      235.      240.      264.      401.
CO - PPM              .57       .44       .43       .52       .59       .52       .53       .48       .36       .44       .60       .76


      GRAND AVERAGE

IRAD - LANGLEY/M      .248
WIND SPEED - MPH     4.60
WIND DIR - DEG     163.
TEMP - DEG C        26.7
RH - %              75.1
O3 - PPM              .048
NO - PPM          ≤   .005
NOX - PPM             .013
HNO3 - PPM        ≤   .006
PAN - PPM             .002
FREON 11 -PPT      253.
CO - PPM              .64
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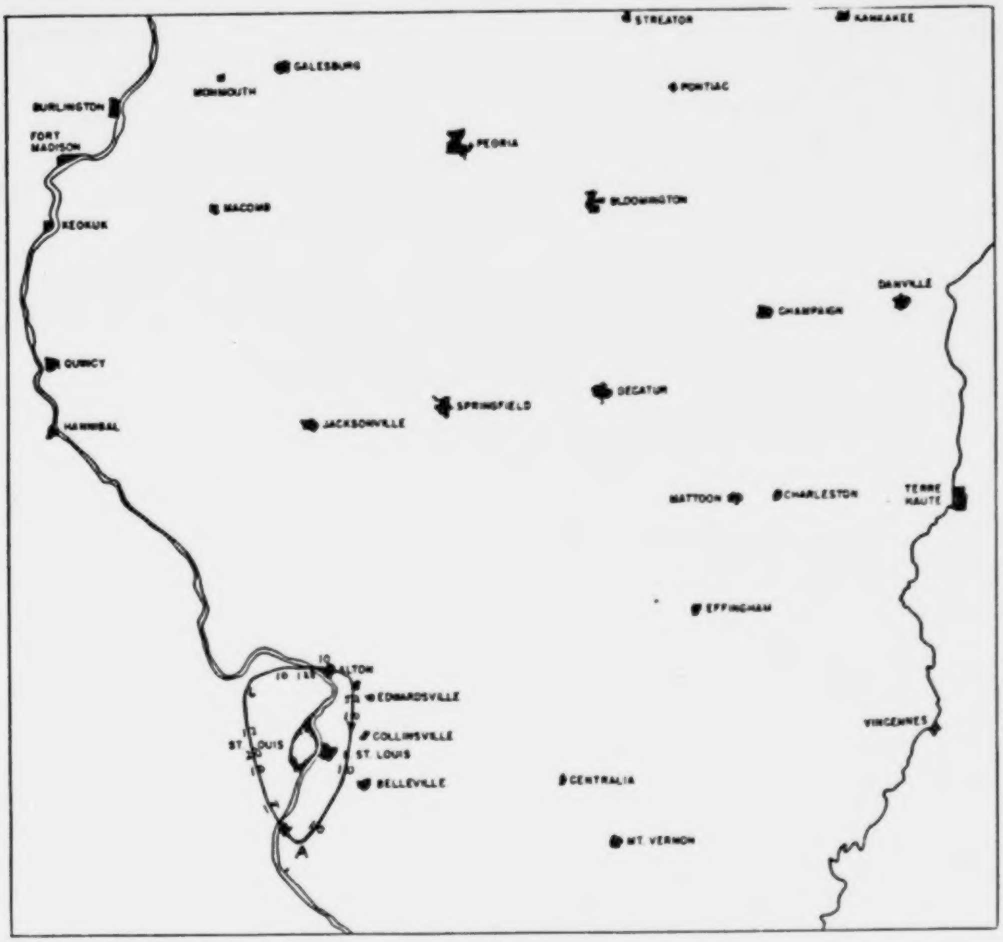
APPENDIX B

FLIGHT MAPS AND VERTICAL PROFILES FROM THE 1977 MIDWEST FIELD PROGRAM

Appendix B provides aircraft flight maps and vertical profiles for the airborne monitoring portion of the 1977 Midwest Field Program. Two maps are shown for each flight; one contains O_3 data, the other shows NO_x results. The vertical profiles are grouped together at the end of the Appendix and are keyed to the flight maps by flight number and date.

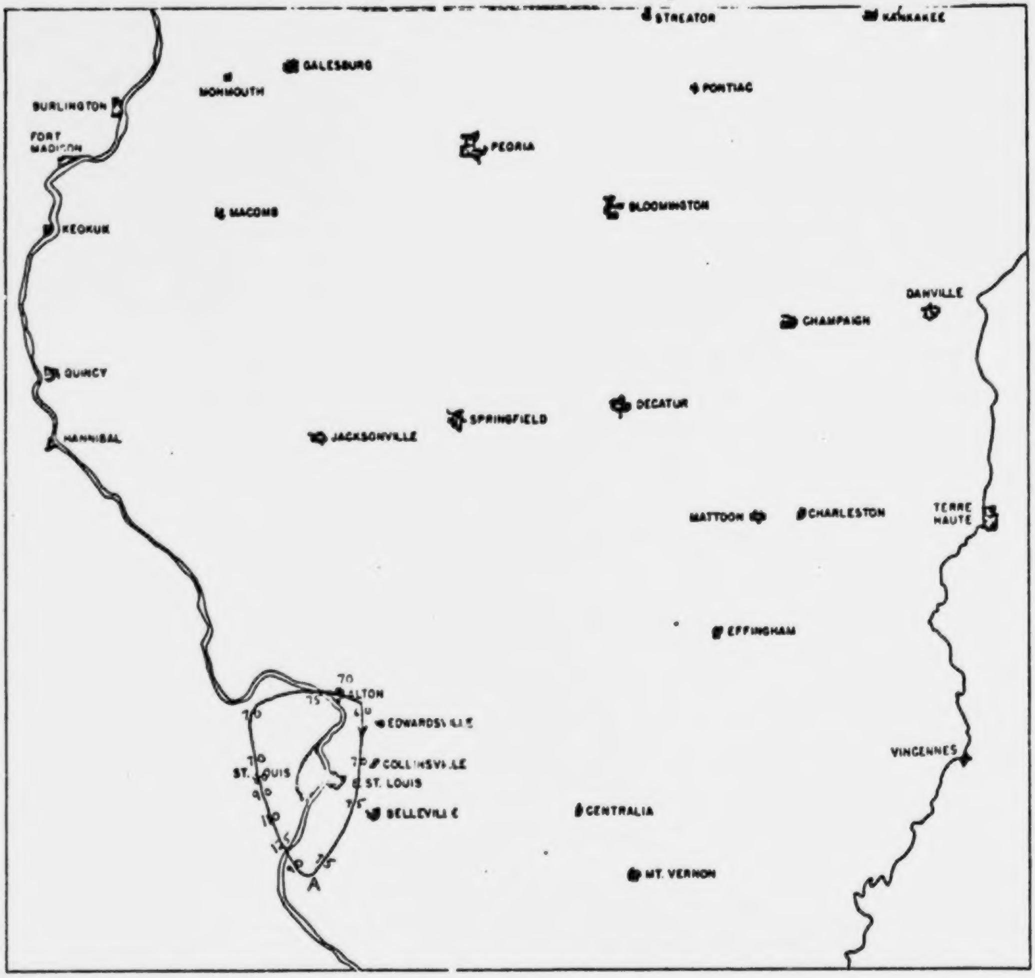
NO_x, ppb
Flight 1
Saturday 7-9-77
Afternoon 12:25 ⟶ 14:02



Spiral
PT. A ⟶ 12,000 ft.

Bag
PT. A @ 5,000 ft.

O_3, ppb Afternoon
12:25 → 14:02
Flight 1
Saturday 7-9-77



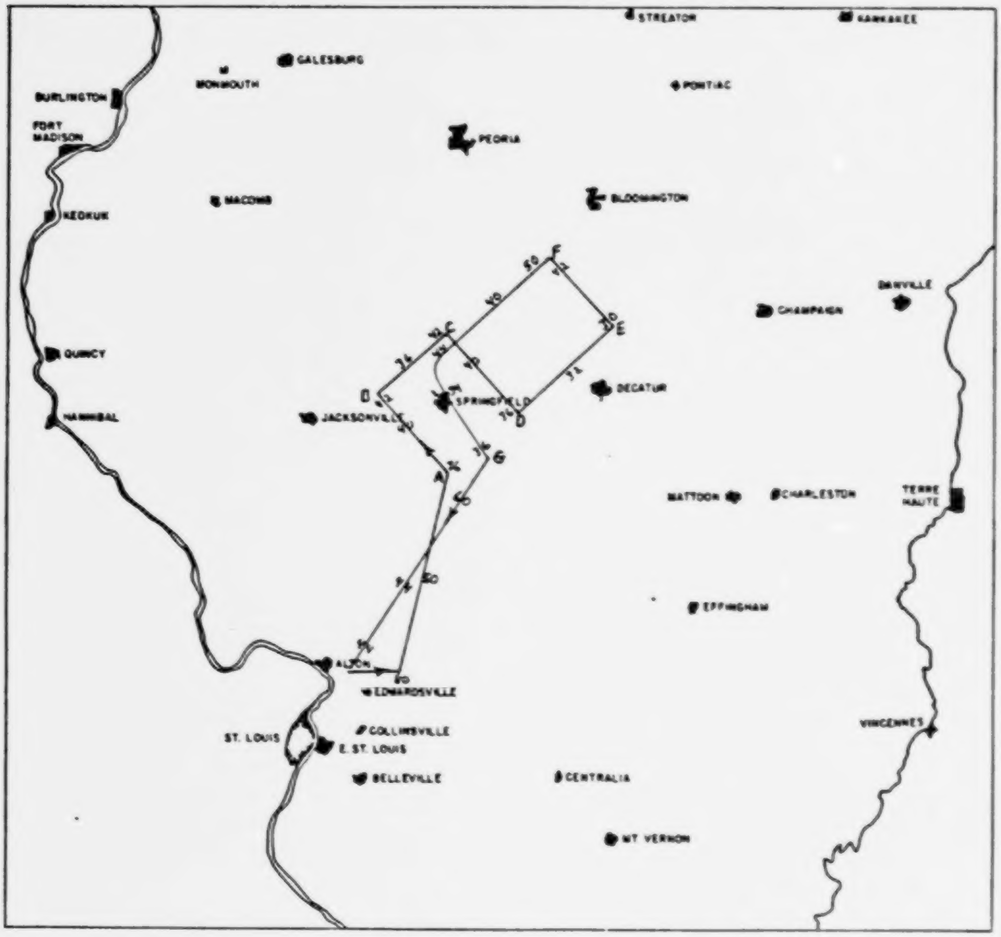
Spiral

Pt. A → 12,000 ft

Bag

PT. A at 12,000 Ft.

O_3, ppb
Flight 2
Tuesday, July 12, 1977
Afternoon 12:45 → 16:20

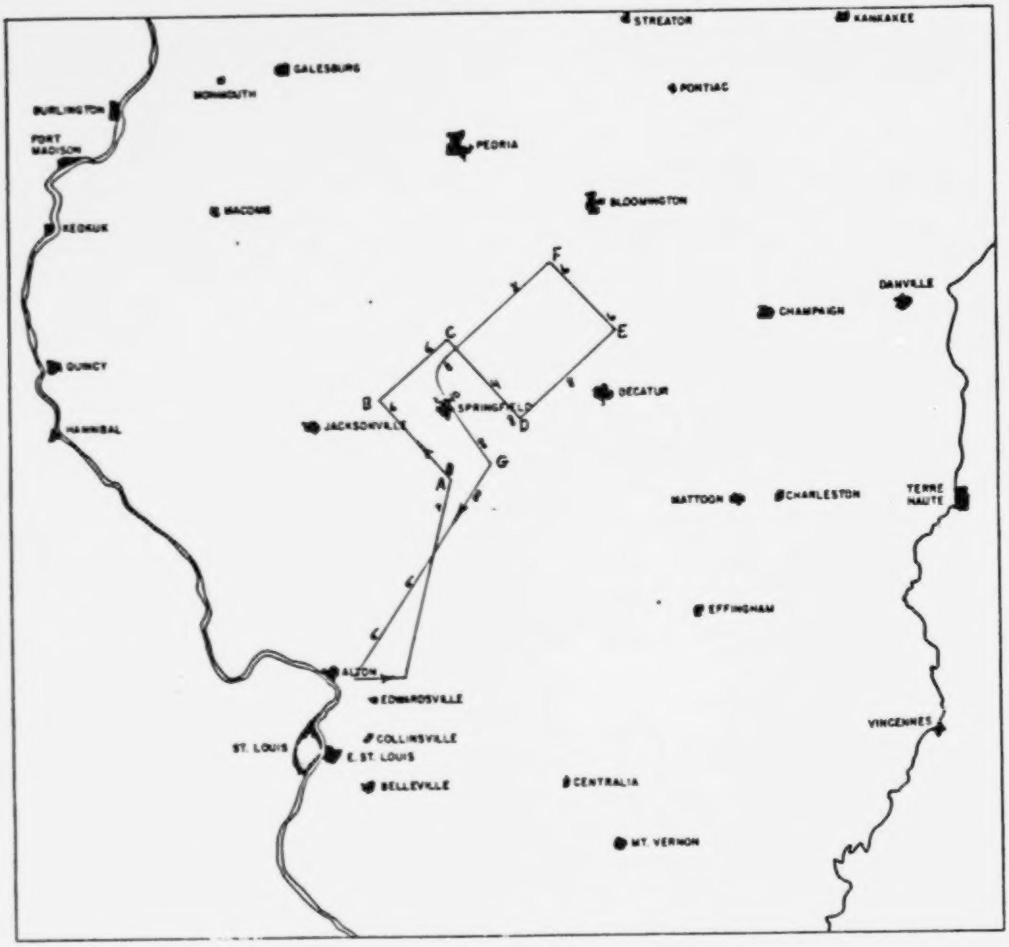


Filters		
No. 1	A →	B
No. 2	C →	D
No. 3	E →	F

Bags		
No. 1	A →	B
No. 2	C →	D
No. 3	E →	F

Spiral
PT. G 2,000 → 20,000 Ft

NO_x, ppb
Flight 2
Tuesday 7-12-77
Afternoon 12:45 — 16:20



Filters

No. 1. A — B
No. 2. C — D
No. 3. E — F

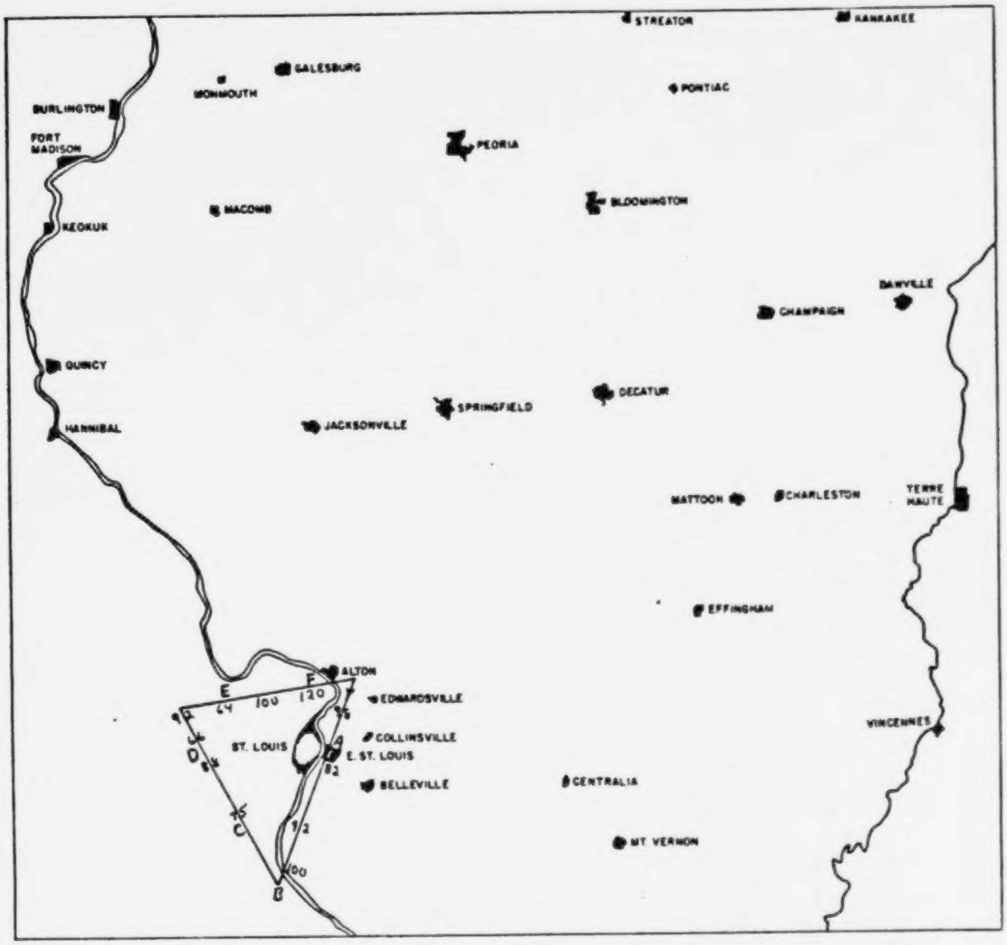
Bags

No. 1. A — B
No. 2. C — D
No. 3. E — F

Spiral

PT. G 2,000 — 20,000 ft.

O_3, ppb
Flight 4
Friday 7-15-77
Afternoon 12:45 → 15:42 PM

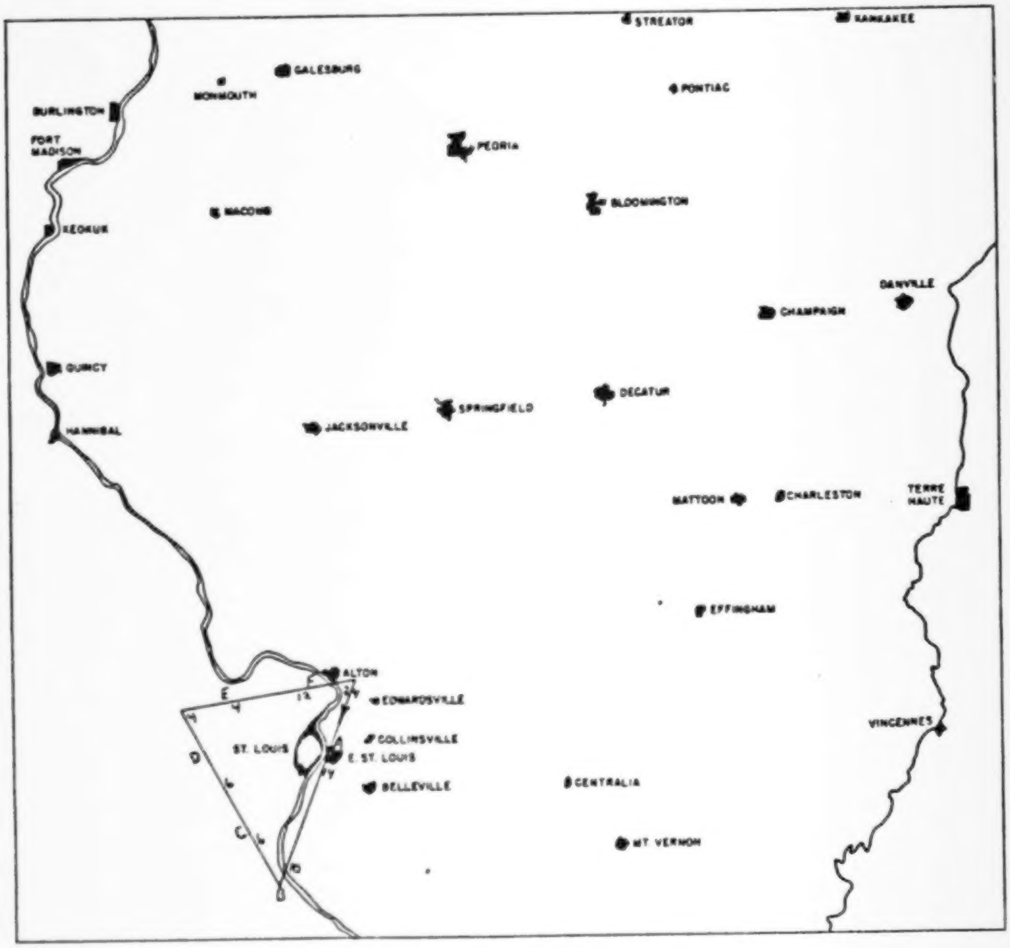


Filter
A → B

Spiral
Pt. B → 20,000 Ft

Bags
No. 1. PT. B - 20,000 ft.
No. 2. PT. B - 15,000 ft.
No. 3. PT. B - 10,000 ft.
No. 4. PT. B - 6,000 ft.
No. 5. PT. B - 3,000 ft.
No. 6. PT. B - 1,000 ft
No. 7. C → D
No. 8. E → F

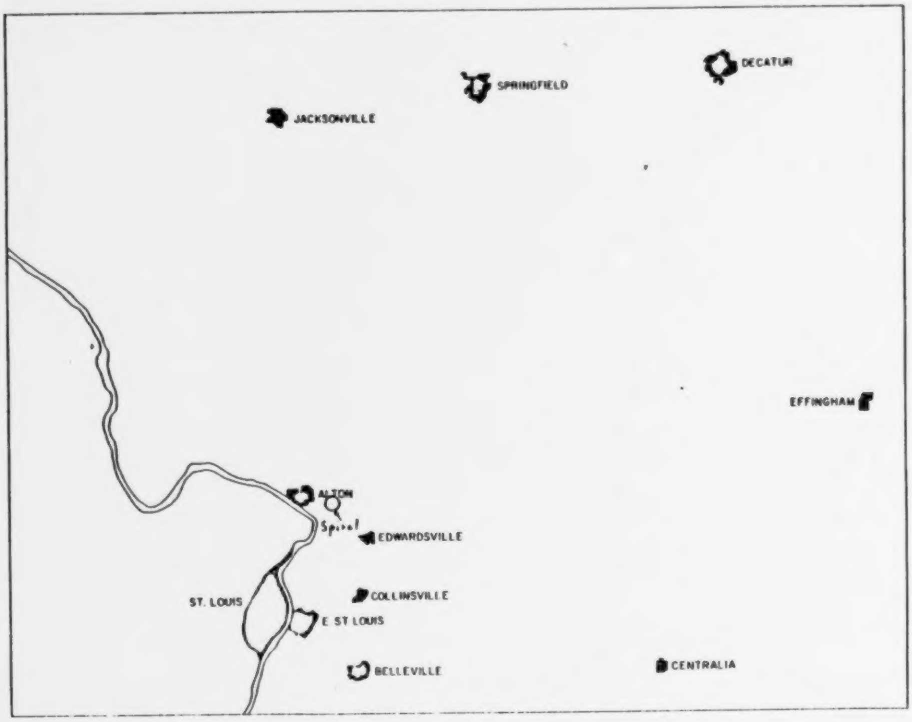
NO_x, ppb
Flight 4
Friday 7-15-77
Afternoon 12:45 → 15:42 PM



Filter	Spiral
A → F	PT. B → 20,000 ft.

No. 1. PT. B - 20,000 ft.
No. 2. PT. B - 15,000 ft.
No. 3. PT. B - 10,000 ft.
No. 4. PT. B - 6,000 ft.
No. 5. PT. B - 3,000 ft.
No. 6. PT. B - 1,000 ft.
No. 7. C → D
No. 8. E → F

Flight 5 - Spiral
Wednesday - 7-20-77
Night - 10:00 → 10:55 p.m.



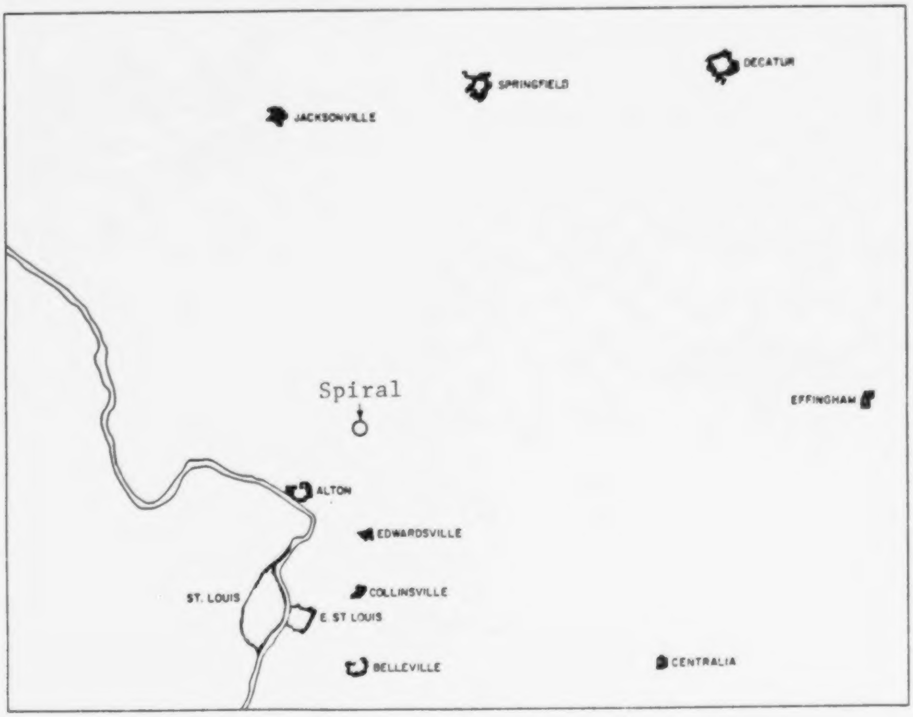
Spiral

2,000 → 10,000 ft

Bags

No. 1.	10,000 ft.	No. 4.	4,000 ft.
No. 2.	6,000 ft.	No. 5.	3,000 ft.
No. 3.	5,000 ft.	No. 6.	2,000 ft.

Flight 6 - Spiral
Thursday 7-21-77
Early Morning 6:05 → 7:23



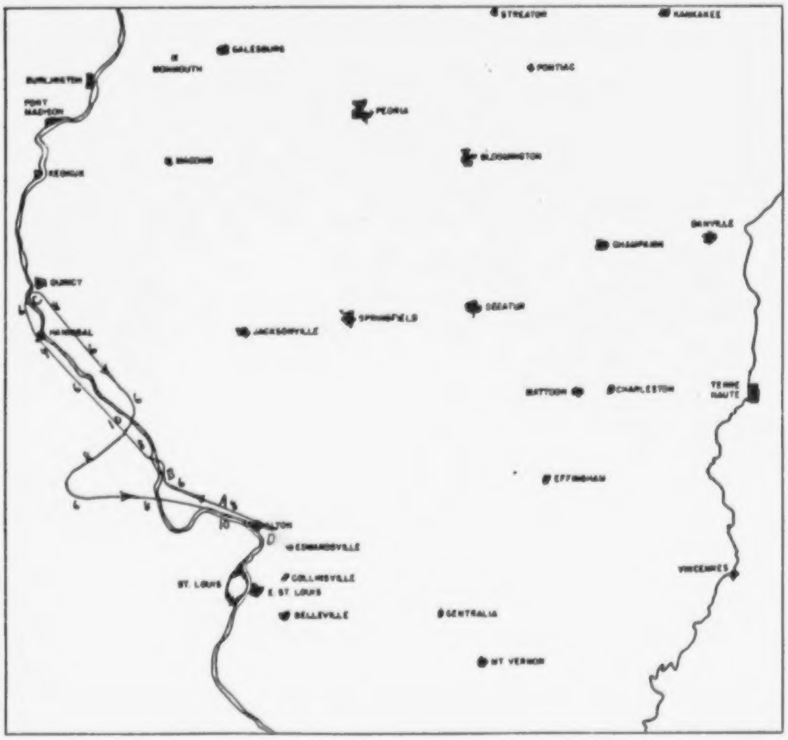
Spiral

1600 → 10,000 ft

Bags

No. 1.	10,000 ft.
No. 2.	6,000 ft.
No. 3.	4,000 ft.
No. 4.	2,000 ft.
No. 5.	1,600 ft.

NO_x, ppb
Flight 7
Thursday 7-21-77
Afternoon 15:05 ⟶ 18:10 PM

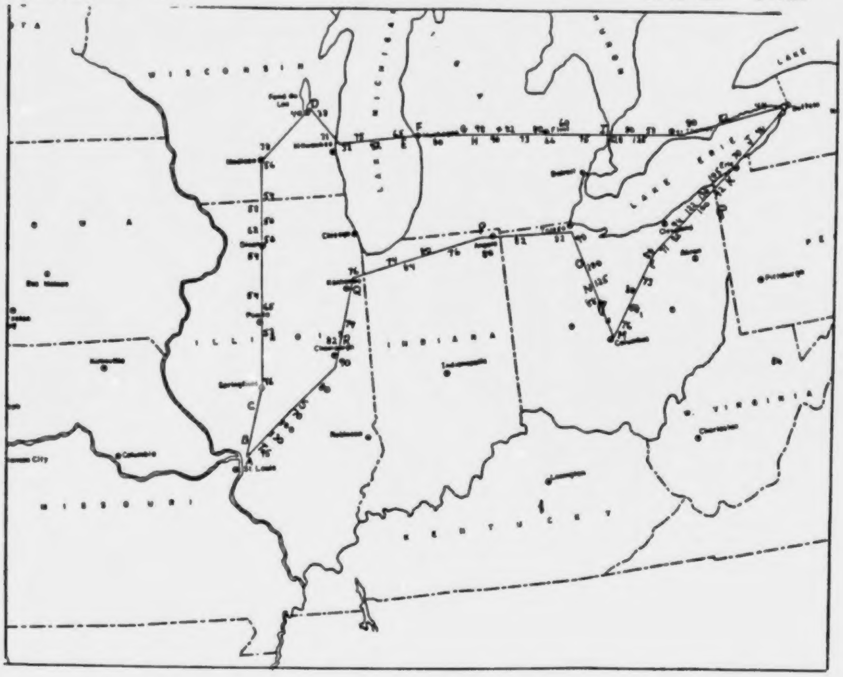


Spirals	Filter	Bags
No. 1. PT. B 1500 ⟶ 6000 ft	PT. A ⟶ D	No. 1. PT. B - 6000 ft
No. 2. PT. C 1800 ⟶ 3500 ft		No. 2. PT. B - 3000 ft
		No. 3. PT. C - 3500 ft

O_3, ppb
Flight 8
Friday 7-22-77
10:00 AM → 1608

O_3, ppb
Flight 9
Saturday 7-23-77
2:00 → 20:40

O_3, ppb
Flight 10
Sunday 7-24-77
8:45 AM → 14:15



Flight 8 A → F

Filter

No. 1. B → F

Spirals

No. 1. PT. C 3,000 → 12,000'
No. 2. PT. D 3,000 → 20,000'

Bags

No. 1. PT. C - 6,500'
No. 2. PT. D - 20,000'
No. 3. PT. E - 1,000' AGL

Flight 9 F → M

Filters

No. 1. F → J
No. 2. J → L

Spiral

No. 1. PT. G 2,000' → 20,000'
No. 2. PT. J 2,000' → 20,000'

Bags

No. 1. PT. G - 11,250'
No. 2. PT. G - 4,500'
No. 3. PT. H - 1,000' AGL
No. 4. PT. I - 1,000' AGL
No. 5. PT. J - 20,000'
No. 6. PT. J - 14,000'
No. 7. PT. J - 2,000'
No. 8. PT. K - 1,000' AGL

Flight 10 M → A

Filters

No. 1. N → Q
No. 2. Q → T

Spiral

No. 1 PT. O 3,000 → 12,000

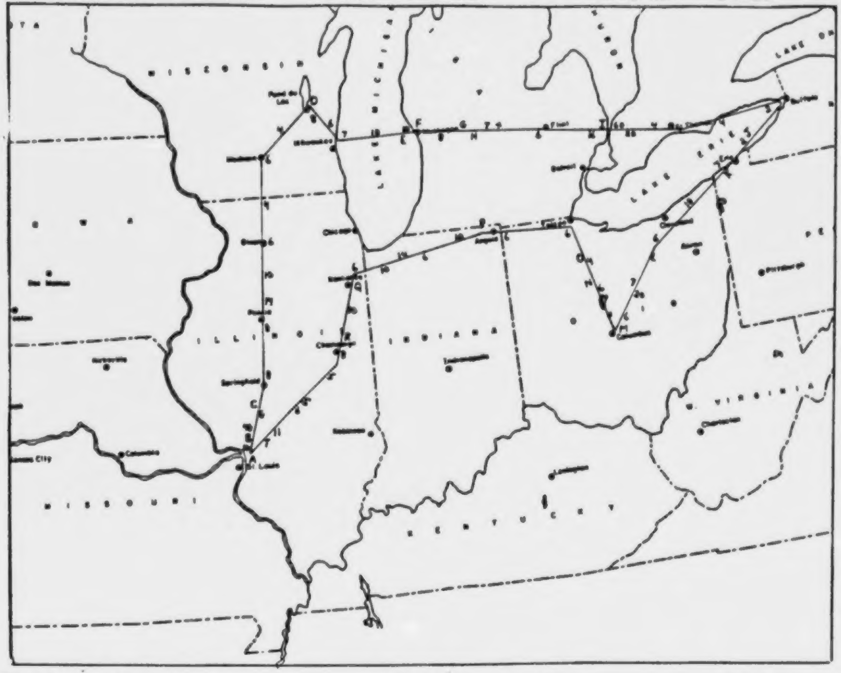
Bags

No. 1. PT. O 2,000'
No. 2. PT. P 1,000' AGL
No. 3. PT. R 1,000' AGL
No. 4. PT. S 1,000' AGL

NO_x, ppb
Flight 8
Friday 7-22-77
10:00 AM → 16:08

NO_x, ppb
Flight 9
Saturday 7-23-77
14:00 → 20:40

NO_x, ppb
Flight 10
Sunday 7-24-77
8:45 AM → 14:15



Flight 8 A → F

Filter

No. 1 B → F

Spirals

No. 1 PT. C 3,000 → 12,000
No. 2 PT. D 3,000 → 20,000

Bags

No. 1. PT C - 6,500'
No. 2. PT D -20,000'
No. 3. PT E - 1,000' AGL

Flight 9 F → M

Filter

No. 1. F → J
No. 2. J → L

Spirals

No. 1 PT. G 2,000 → 20,000
No. 2 PT. J 2,000' → 20,000

Bags

No. 1. PT. G - 11,250'
No. 2. PT. G - 4,500'
No. 3. PT. H - 1,000' AGL
No. 4. PT. I - 1,000' AGL
No. 5. PT. J - 20,000'
No. 6. PT. J - 14,000
No. 7. PT. J - 2,000'
No. 8. PT. K - 1,000' AGL

Flight 10 M — A

Filter

No. 1. N → Q
No. 2. Q → T

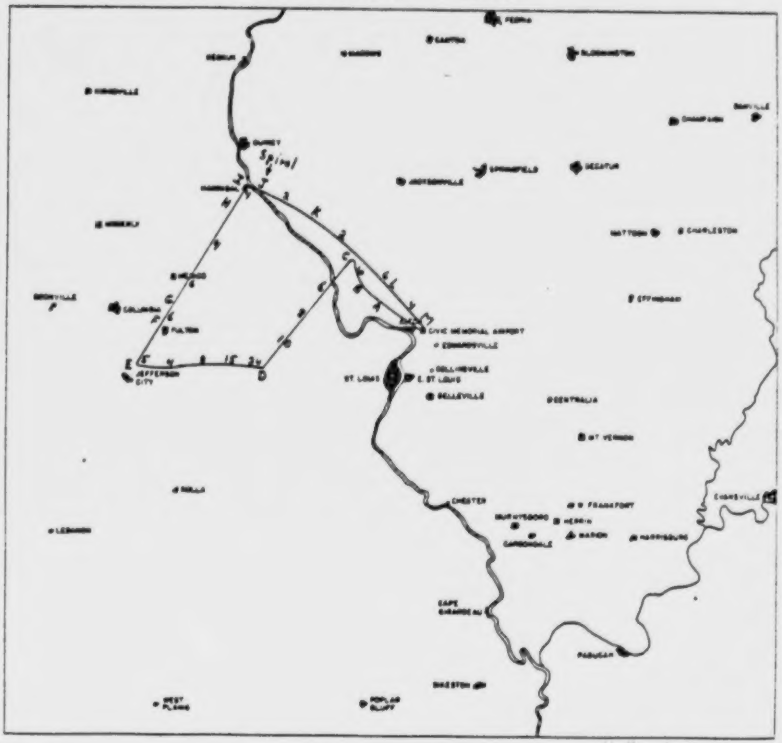
Spiral

No. 1. PT. O 3,000 → 12,000

Bags

No. 1. PT. O 2,000'
No. 2. PT. P 1,000' AGL
No. 3. PT. R 1,000' AGL
No. 4. PT. S 1,000' AGL

NO_x, ppb
Flight 12
Wednesday 7-27-77
Afternoon 16:18 → 18:43

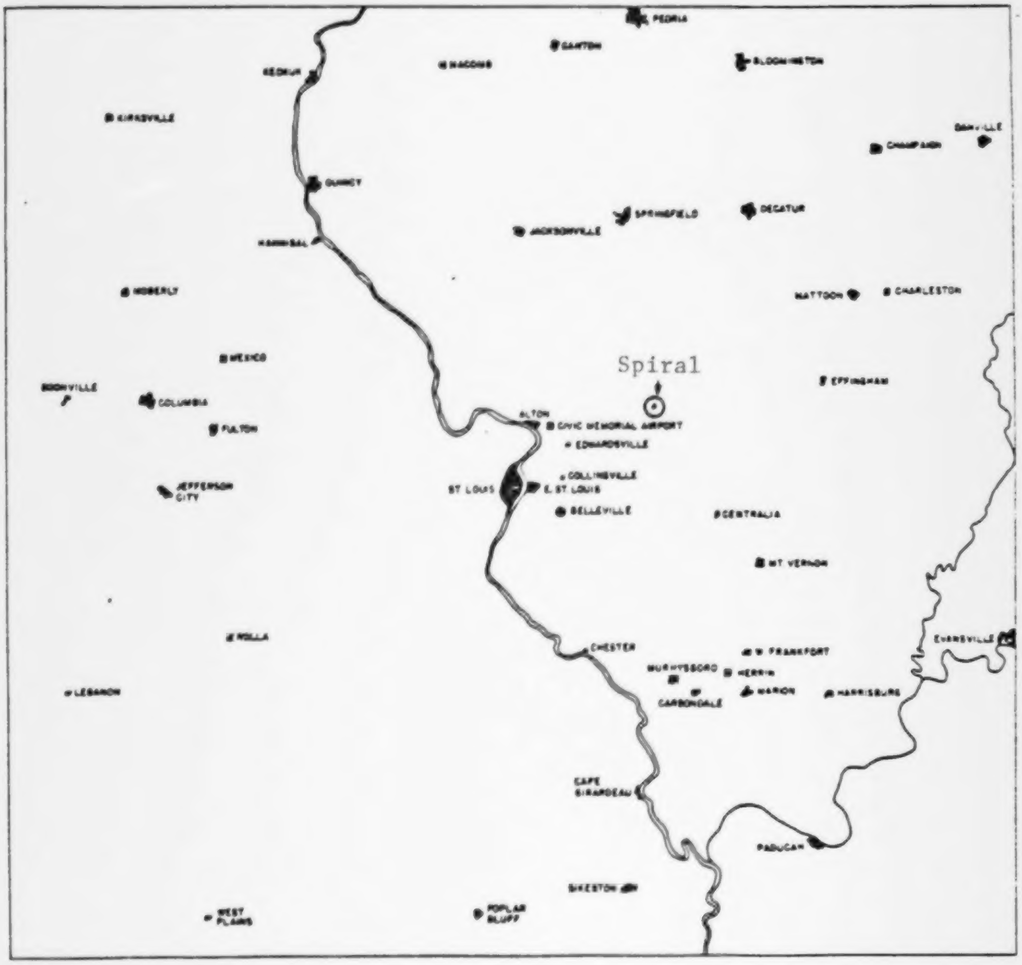


Filters	Bags	Altitudes
No. 1. C → D	No. 1. A → B	J → K 6,300 ft.
No. 2. E → I	No. 2. C → D	K → M 3,400 ft.
	No. 3. E → H	
	No. 4. F → G	
	No. 5. PT. J 8,500 ft.	
	No. 6. PT. J 6,300 ft.	
	No. 7. PT. L 3,400 ft.	

Spiral

PT. J. 1,500 → 8,500 ft.

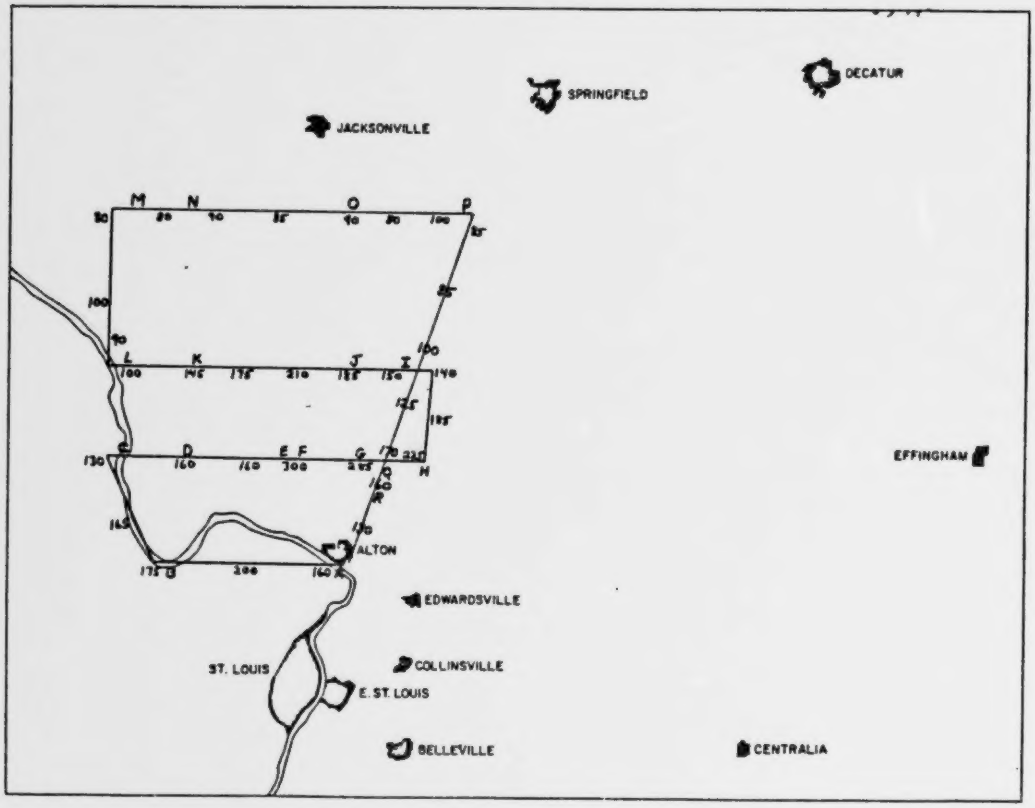
Flight 13
Thursday 7-28-77
Morning 7:08 ⟶ 9:29 AM



Bags

No. 1. - 20,000 ft.
No. 2. - 15,000 ft.
No. 3. - 10,000 ft.
No. 4. - 6,000 ft.
No. 5. - 3,000 ft.
No. 6. - 1,500 ft.

O_3, ppb
Flight 14
Thursday 7-28-77
Afternoon 14:35 ⟶ 16:40



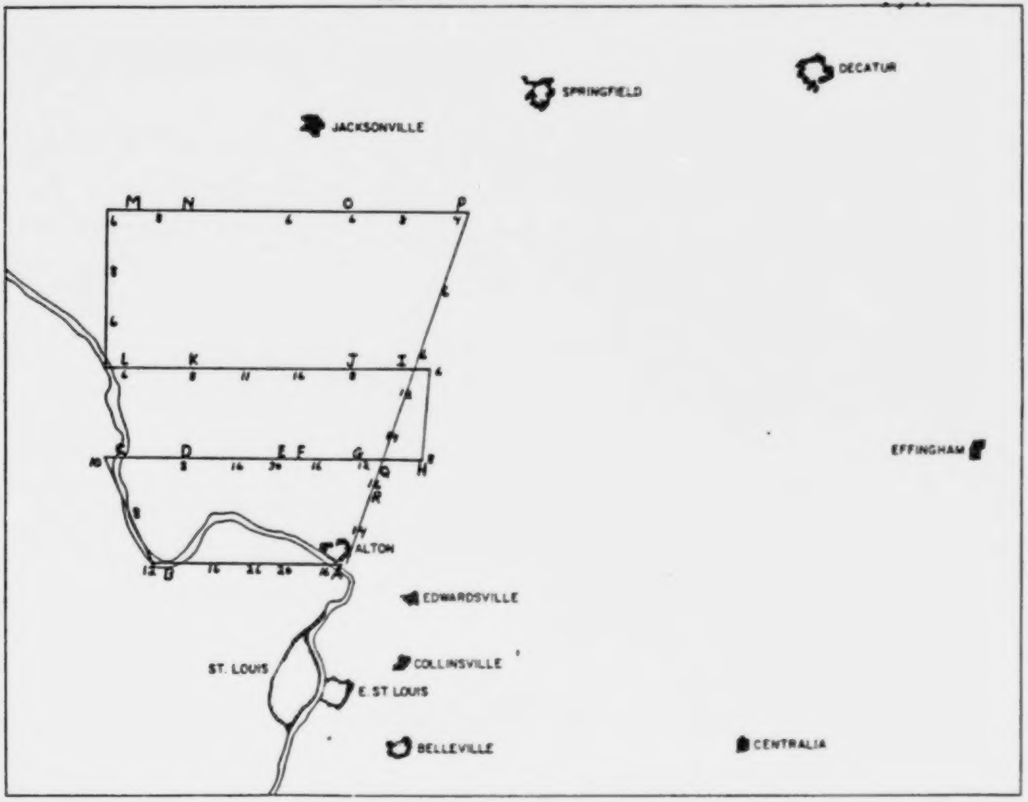
Filters

No. 1. A ⟶ B
No. 2. C ⟶ H
No. 3. I ⟶ L
No. 4. M ⟶ P

Bags

No. 1. A ⟶ B
No. 2. D ⟶ G
No. 3. E ⟶ F
No. 4. J ⟶ K
No. 5. N ⟶ O
No. 6. Q ⟶ R

NO_x, ppb
Flight 14
Thursday 7-28-77
Afternoon 14:35 → 16:40



Filters

No. 1. A → B
No. 2. C → H
No. 3. I → L
No. 4. M → P

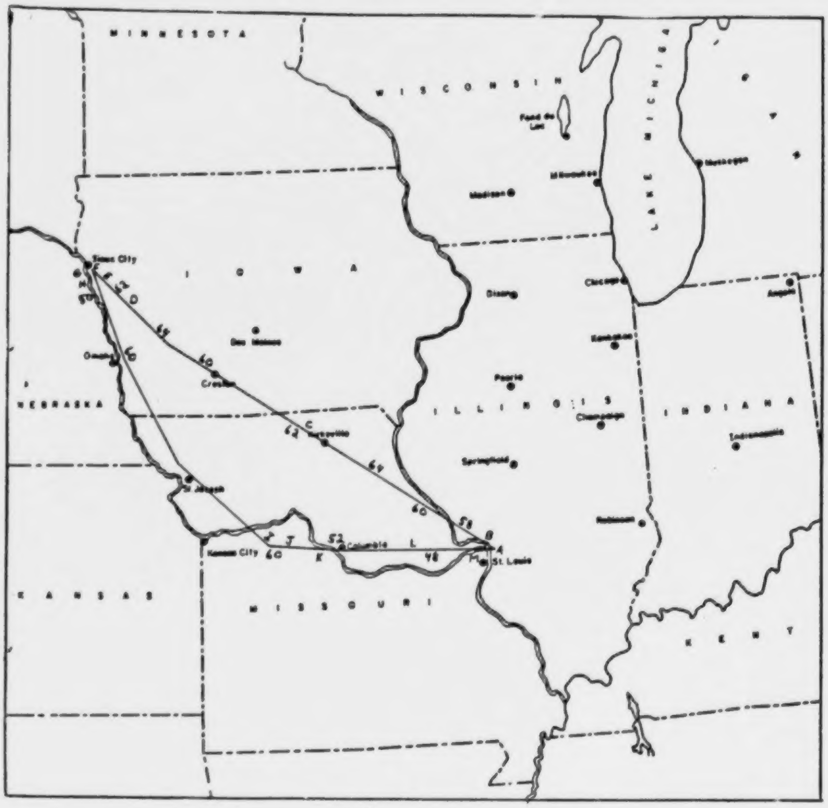
Bags

No. 1. A → B
No. 2. D → G
No. 3. E → F
No. 4. J → K
No. 5. N → O
No. 6. Q → R

O_3, ppb

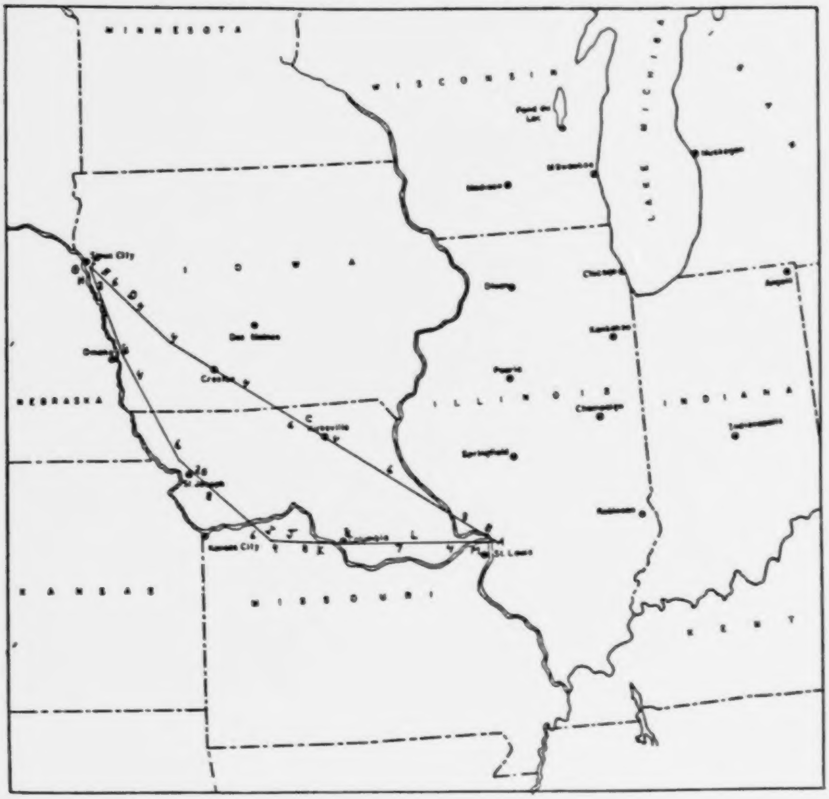
Flight 15
Friday 7-29-77
10:50 AM → 13:52 PM

Flight 16
Friday 7-29-77
15:10 → 18:21 PM



Flight 15	Filter	Bag	Spiral
A → F	B → E	PT. C	PT. D 2,500' → 12,000
Flight 16	**Filter**	**Bag**	**Spiral**
F → A	No. 1. G → I No. 2. J → M	No. 1 PT. H No. 2 PT. K	PT. L 1,800' → 8,000'

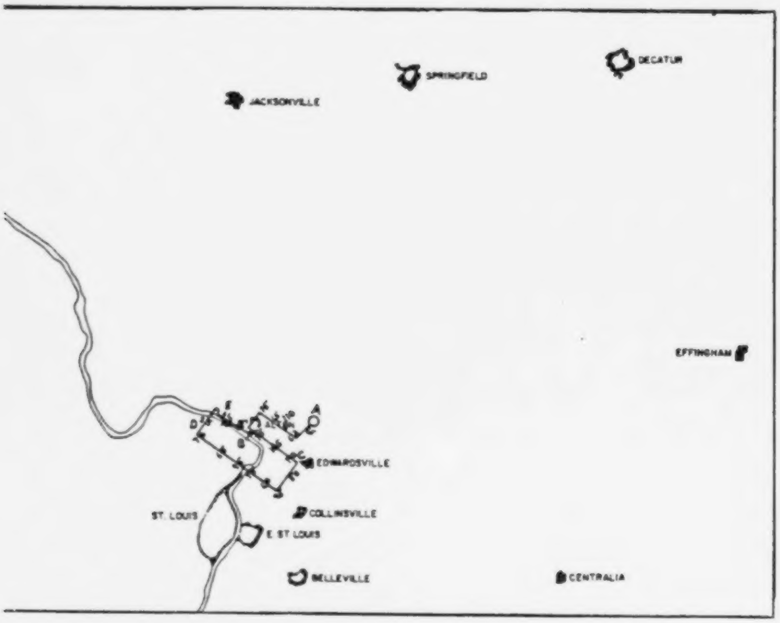
NO_x, ppb	Flight 15	Flight 16
	Friday 7-29-77	Friday 7-29-77
	10:50 → 13:52 PM	15:10 → 18:21 PM



Flight 15	Filter	Bag	Spiral
A → F	B → E	PT. C	PT. D. 2,500 → 12,000'

Flight 16	Filters	Bags	Spiral
F → A	No. 1. G → I No. 2. J → M	No. 1. PT. H No. 2. PT. K	PT. L. 1,800 → 8,000'

O_3, ppb
Flight 17
Saturday 7-30-77
Morning 10:10 ⟶ 11:09



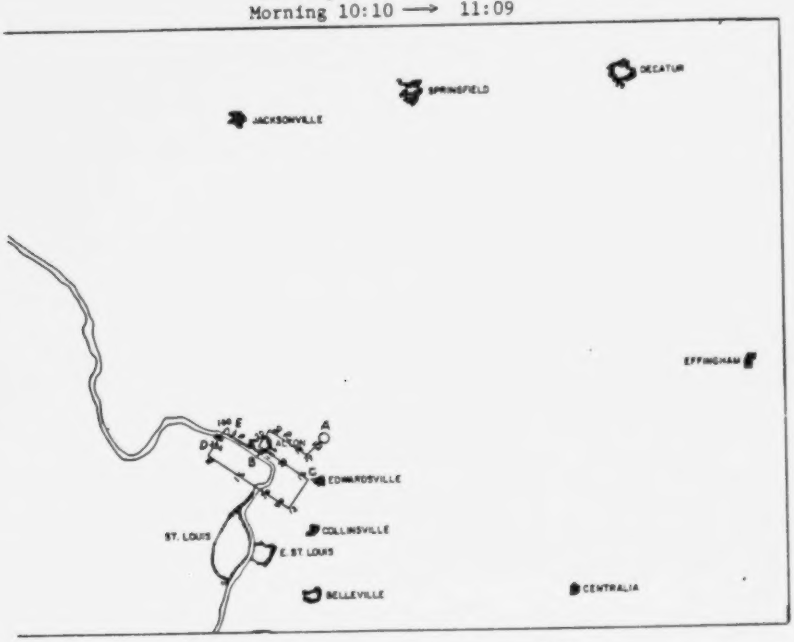
Bags

No. 1. B ⟶ C
No. 2. D ⟶ E

Spiral

PT. A. 1,500 → 3,500 ft.

NO_x, ppb
Flight 17
Saturday 7-30-77
Morning 10:10 ⟶ 11:09



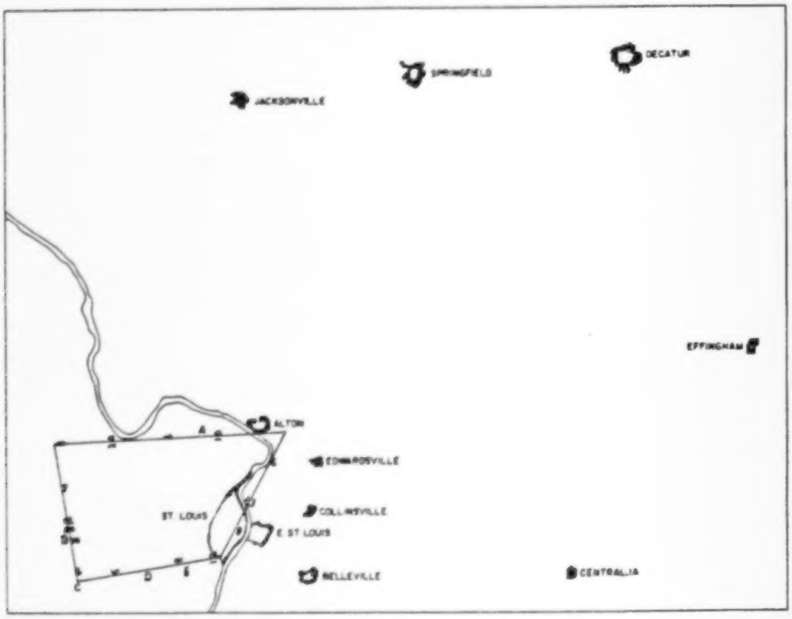
Spiral

PT. A 1,500 ⟶ 3,500 ft.

Bags

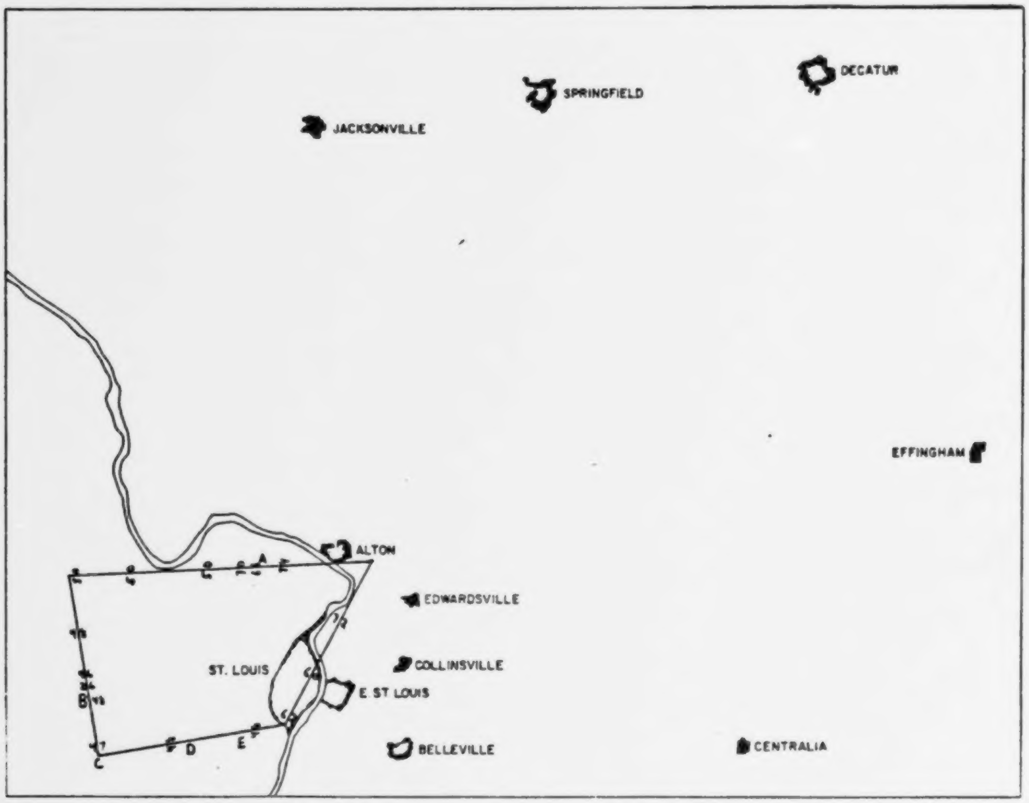
No. 1. - B ⟶ C
No. 2. - D ⟶ E

NO_x, ppb
Flight 18
Saturday 7-30-77
Afternoon 14:41 ⟶ 16:05



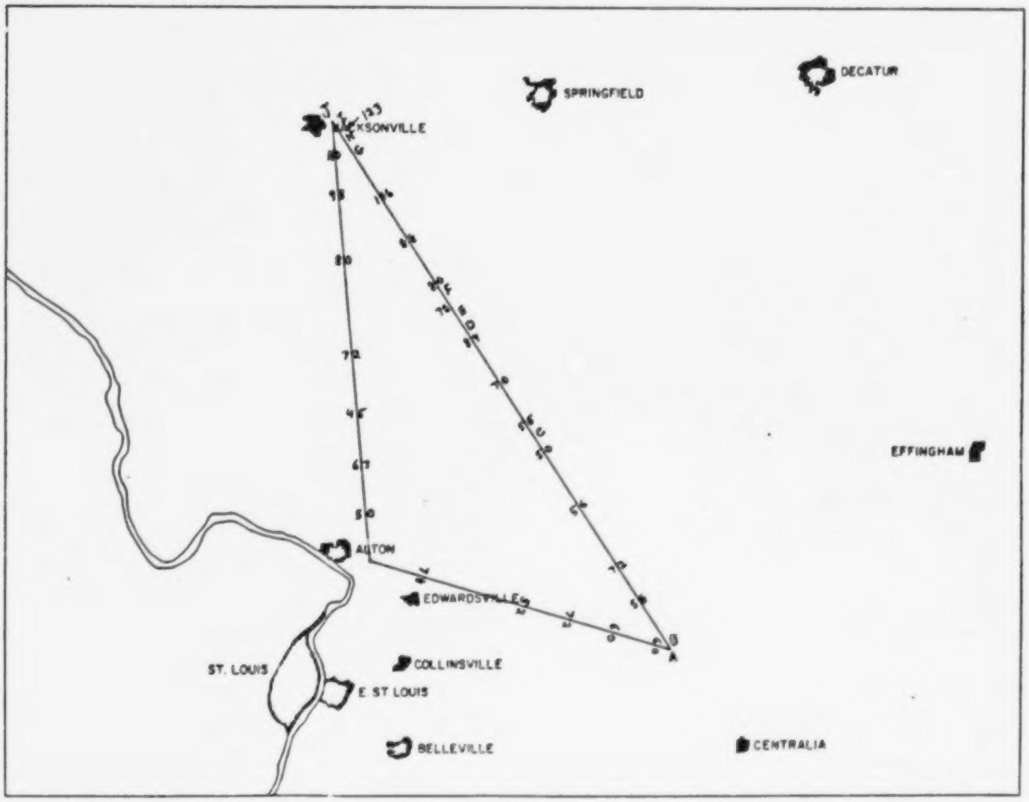
Filter	Spiral	Bag
A ⟶ E	B ⟶ 8,000 ft	C ⟶ D

O_3, ppb
Flight 18
Saturday 7-30-77
Afternoon 14:41 → 16:05



Filter	Spiral	Bag
A → E	B → 8,000 ft	C → D

O_3, ppb
Flight 19
Saturday 7-30-77
Afternoon 16:36 ⟶ 19:03



Filter

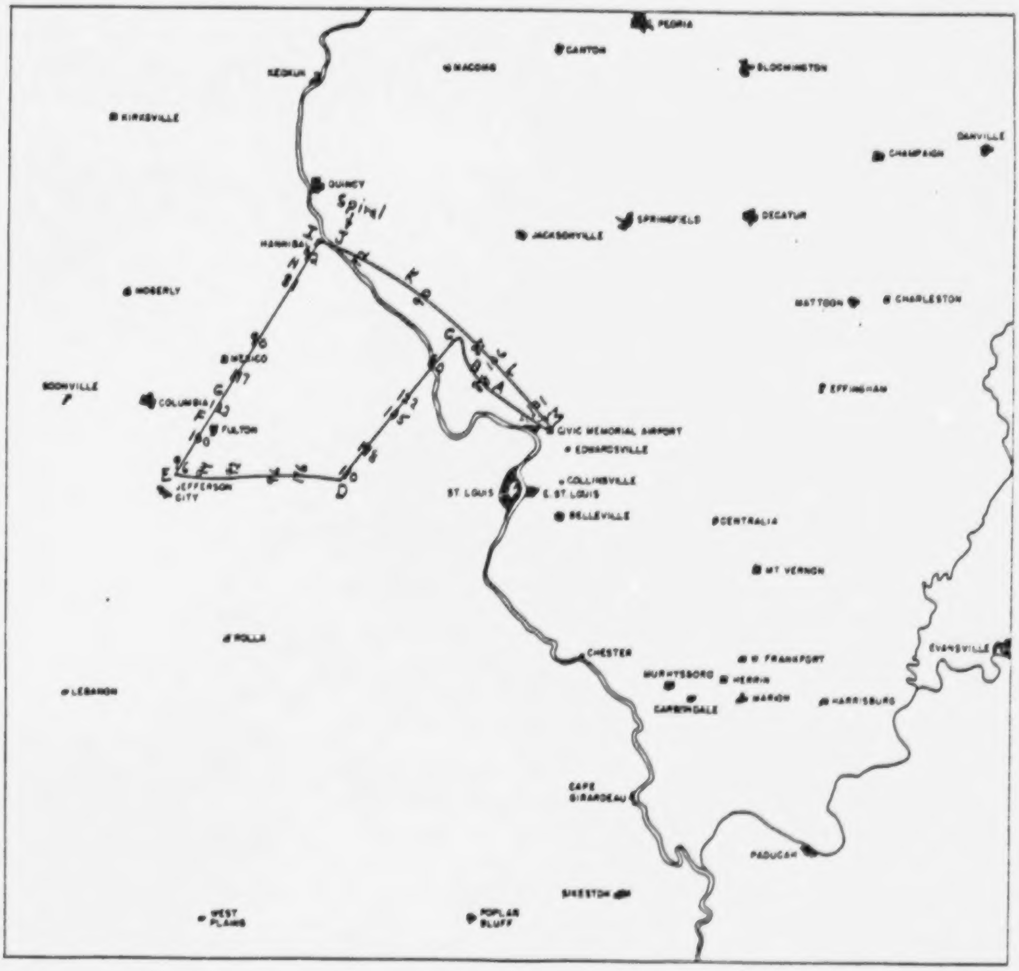
B ⟶ J

Spirals

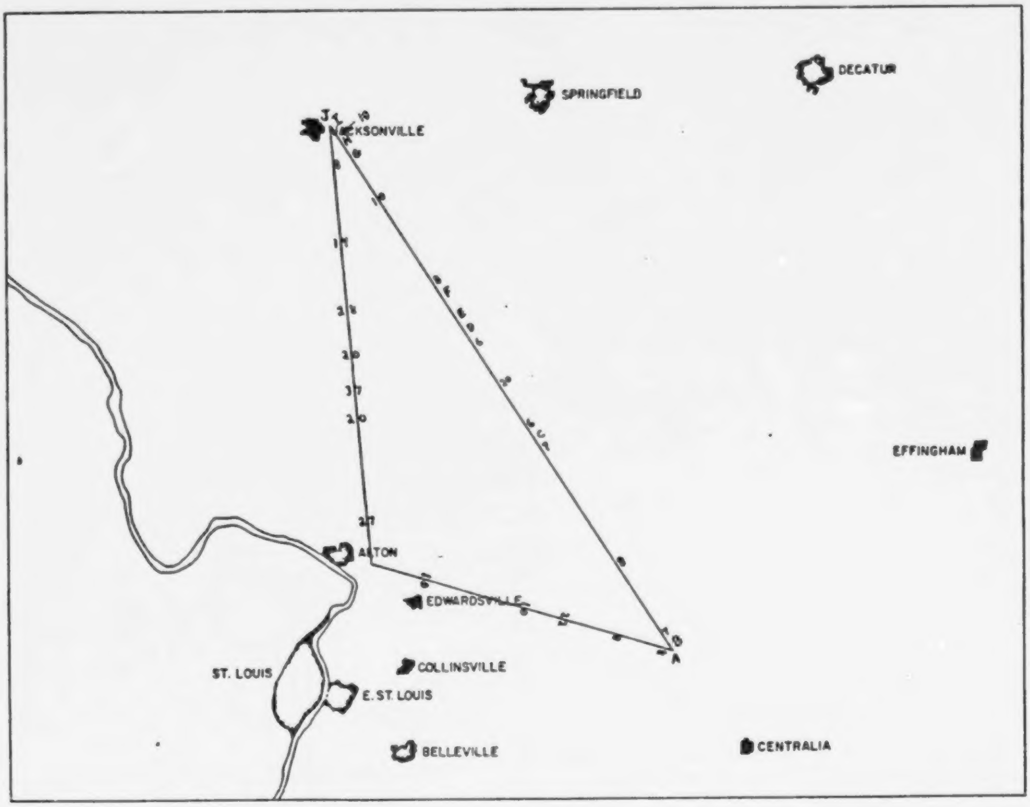
No. 1. PT. A - 6,000 ft.
No. 2. PT. C - 6,500 ft.
No. 3. PT. F - 6,500 ft.
No. 4. PT. G - 6,500 ft.

Bags

No. 1. D ⟶ E
No. 2. PT. F. 5,000 ⟶ 3,000 ft
No. 3. H ⟶ I

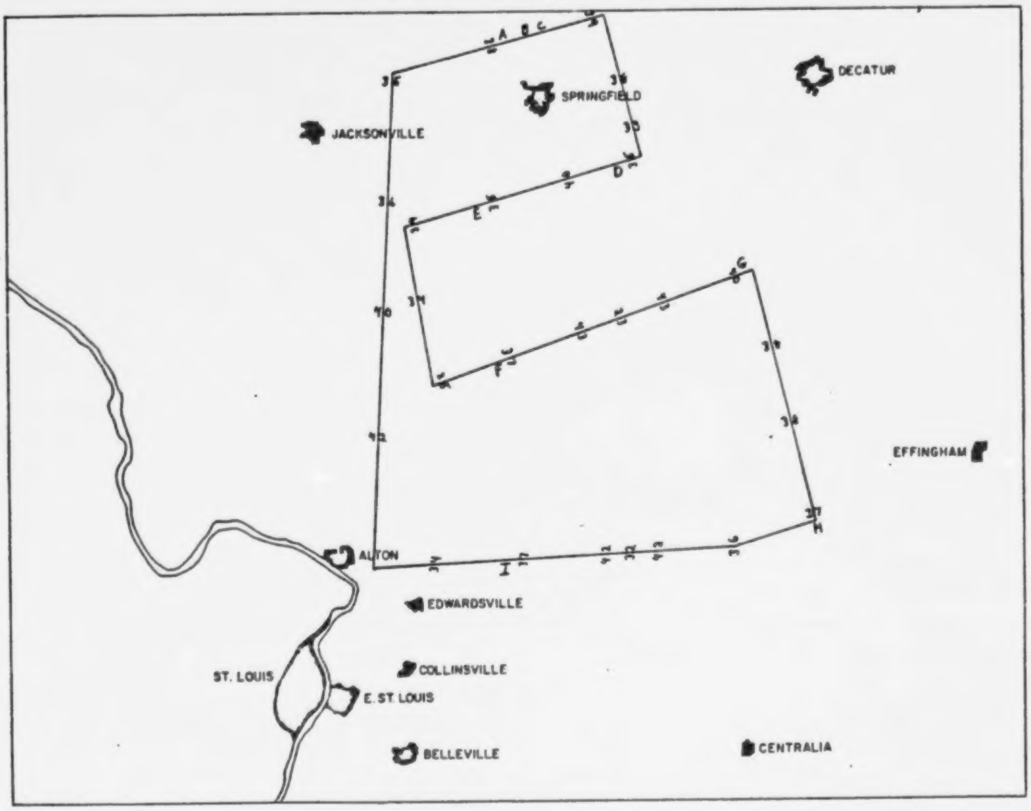

PEORIA
KEOKUK
MACOMB
CANTON
BLOOMINGTON
KIRKSVILLE
DANVILLE
CHAMPAIGN
QUINCY
Spiral
HANNIBAL
JACKSONVILLE
SPRINGFIELD
DECATUR
MOBERLY
MATTOON
CHARLESTON
MEXICO
BOONVILLE
COLUMBIA
FULTON
EFFINGHAM
CIVIC MEMORIAL AIRPORT
EDWARDSVILLE
COLLINSVILLE
JEFFERSON CITY
ST LOUIS
E. ST LOUIS
BELLEVILLE
CENTRALIA
MT VERNON
ROLLA
CHESTER
W FRANKFORT
MURPHYSBORO
HERRIN
EVANSVILLE
LEBANON
CARBONDALE
MARION
HARRISBURG
CAPE GIRARDEAU
PADUCAH
SIKESTON
WEST PLAINS
POPLAR BLUFF
A
B
C
D
E
F
G
H
I
J
K
L
M
90
97
100
110
112
105

NO_x, ppb
Flight 19
Saturday 7-30-77
Afternoon 16:36 ⟶ 19:03



Filters	Spirals	Bags
B ⟶ J	No. 1. PT. A - 6,000 ft.	No. 1. D ⟶ E
	No. 2. PT. C - 6,500 ft.	No. 2. PT. F
	No. 3. PT. F - 6,500 ft.	5,000 ⟶ 3,000 ft
	No. 4. PT. G - 6.500 ft.	No. 3. H ⟶ I

O_3, ppb
Flight 20
Monday 8-1-77
Early Afternoon 11:37 → 13:54



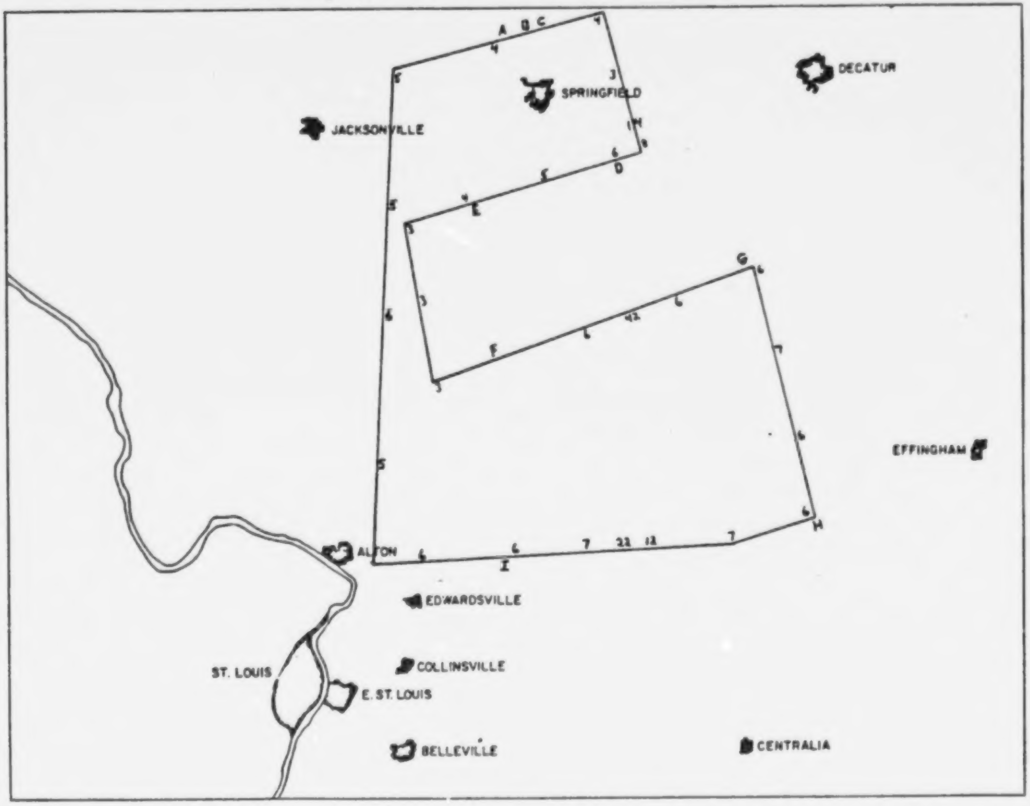
Spiral

PT. A → 6,500 ft.

Bags

No. 1. B → C
No. 2. D → E
No. 3. F → G
No. 4. H → I

NO_x, ppb
Flight 20
Monday 8-1-77
Early Afternoon 11:37 → 13:54



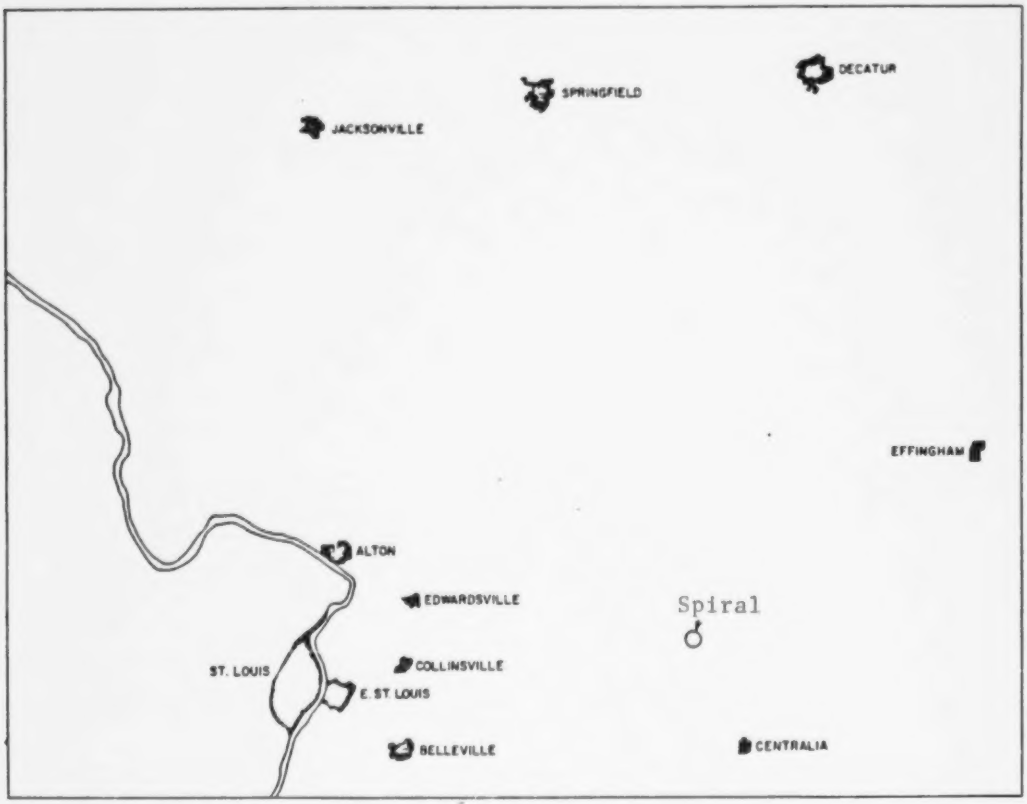
Spiral

PT. A — 6,500 ft.

Bags

No. 1. B → C
No. 2. D → E
No. 3. F → G
No. 4. H → I

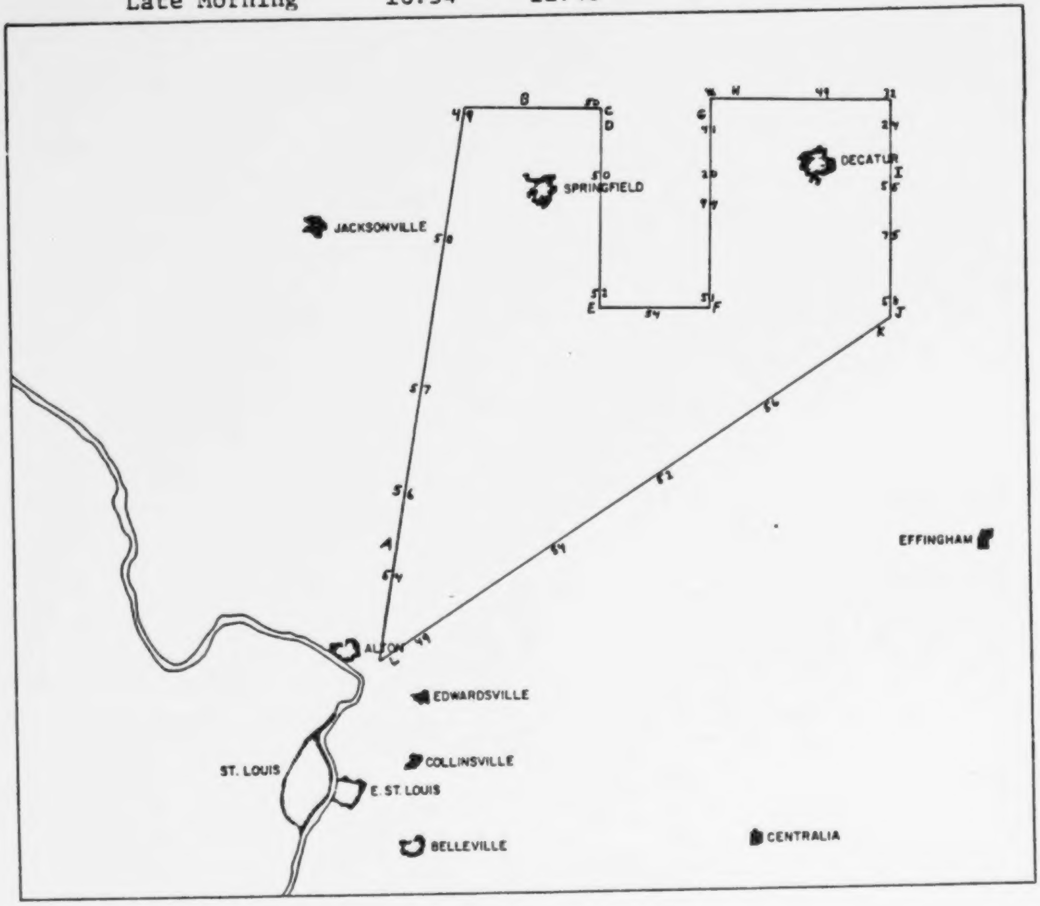
Flight 21
Monday 8-1-77
Night 20:08 → 22:09



Bags

No. 1.	20,000 ft.
No. 2.	15,000 ft.
No. 3.	10,000 ft.
No. 4.	6,000 ft.
No. 5.	3,000 ft.
No. 6.	1,600 ft.

O_3, ppb
Flight 22
Wednesday 8-3-77
Late Morning 10:54 — 12:48



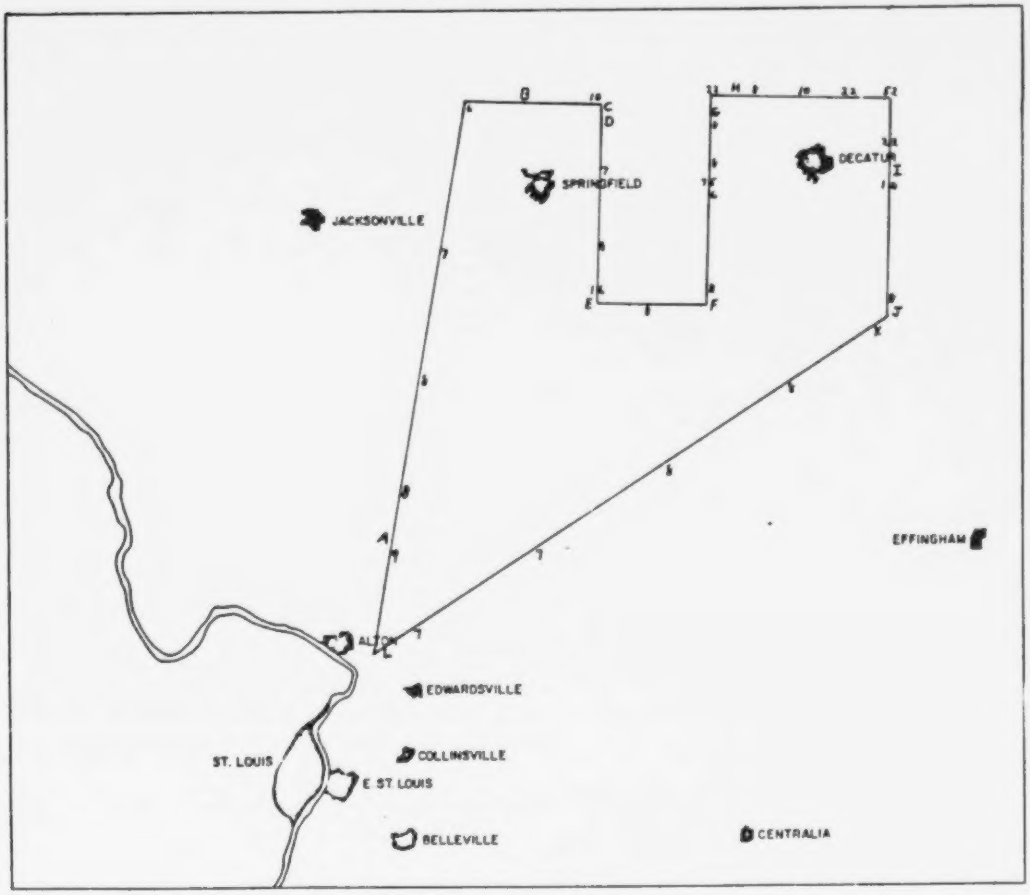
Filters

No. 1. A ⟶ B
No. 2. D ⟶ H
No. 3. K ⟶ L

Bags

No. 1. C ⟶ E
No. 2. F ⟶ G
No. 3. I ⟶ J

NO$_x$, ppb
Flight 22
Wednesday 8-3-77
Late Morning 10:54 → 12:48



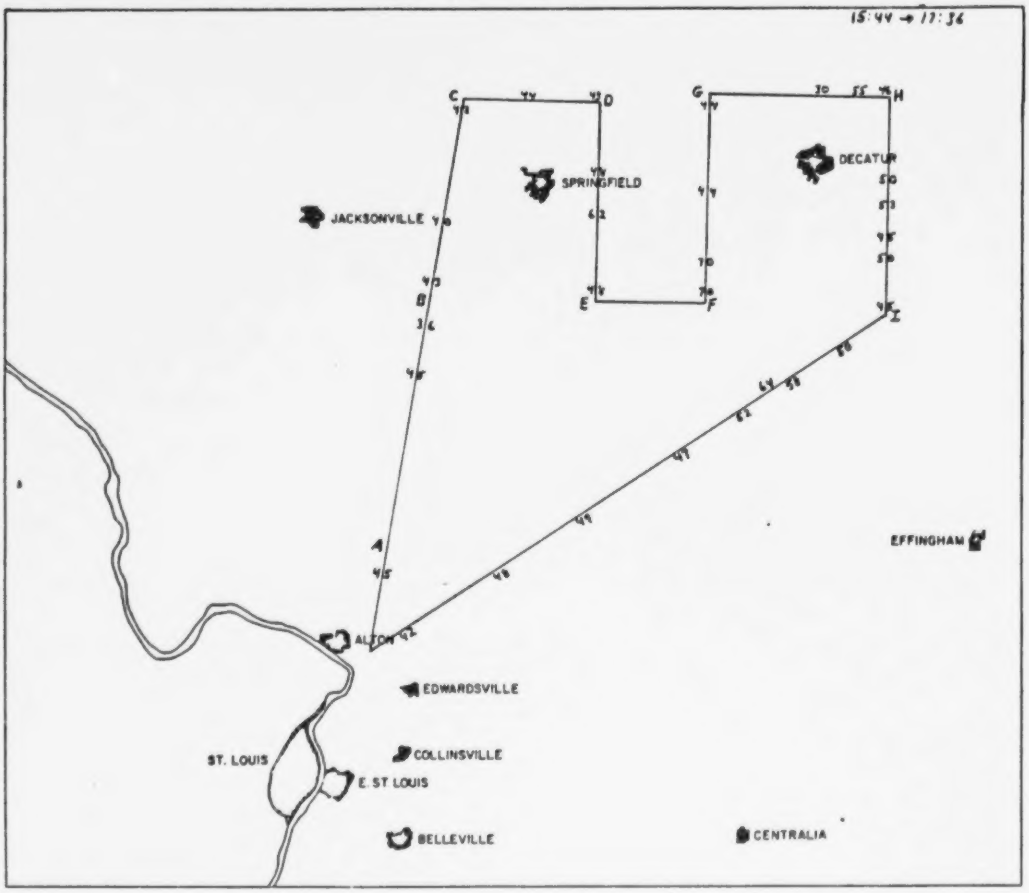
Filters

No. 1. A → B
No. 2. D → H
No. 3. K → L

Bags

No. 1. C → E
No. 2. F → G
No. 3. I → J

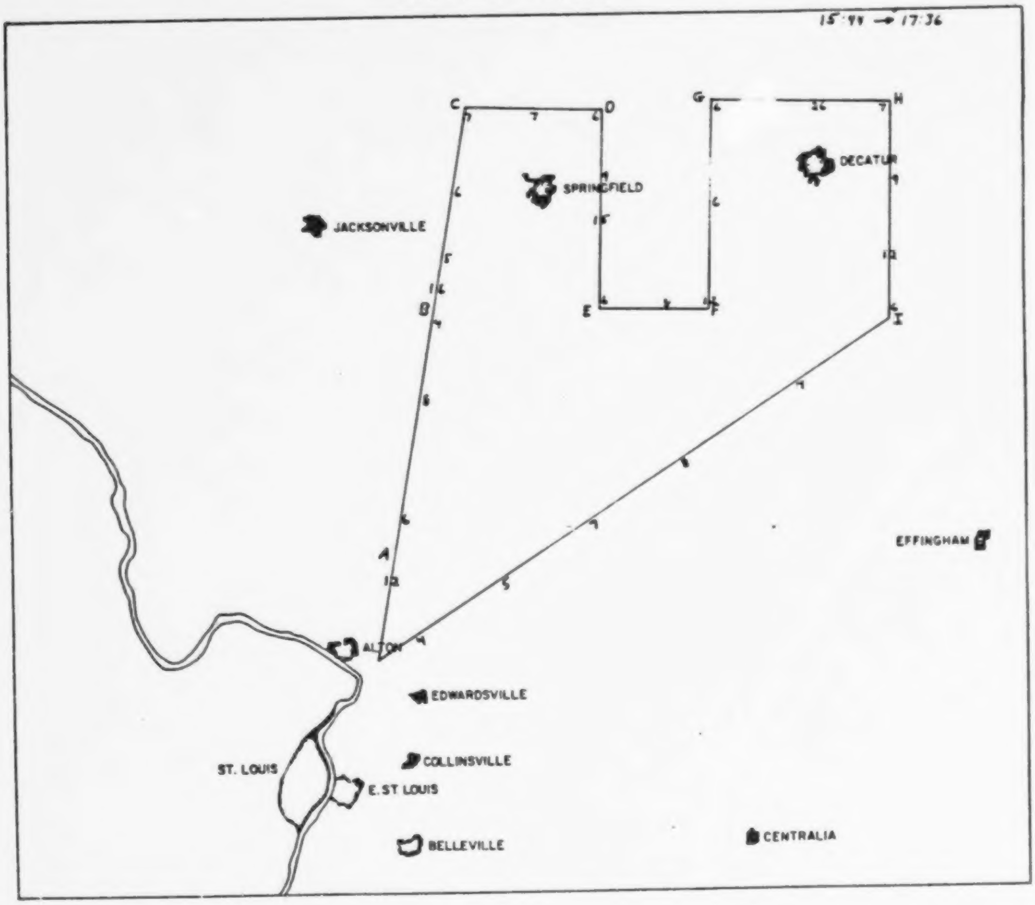
O_3, ppb
Flight 23
Wednesday 8-3-77
15:44 ⟶ 17:36



Filters	
No. 1.	A ⟶ C
No. 2.	D ⟶ G

Bags	
No. 1.	B ⟶ C
No. 2.	D ⟶ E
No. 3.	F ⟶ G
No. 4.	H ⟶ I

NO_x, ppb
Flight 23
Wednesday 8-3-77
15:44 ⟶ 17:36



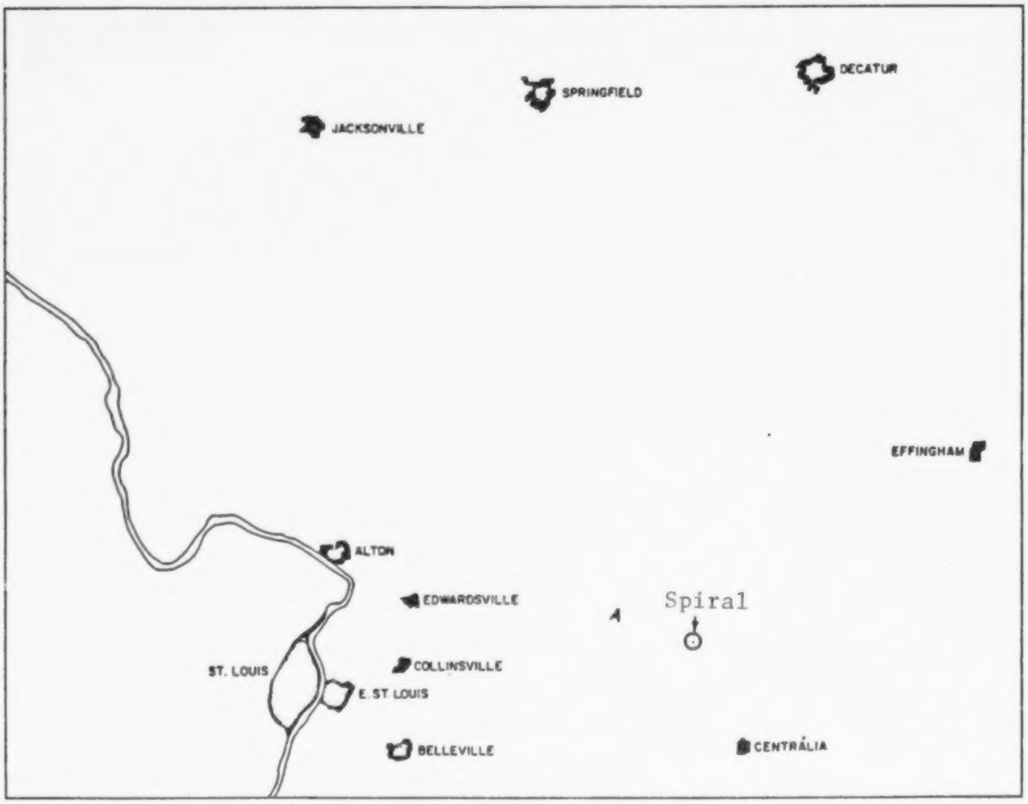
Filters

No. 1. A ⟶ C
No. 2. D ⟶ G

Bags

No. 1. B ⟶ C
No. 2. D ⟶ E
No. 3. F ⟶ G
No. 4. H ⟶ I

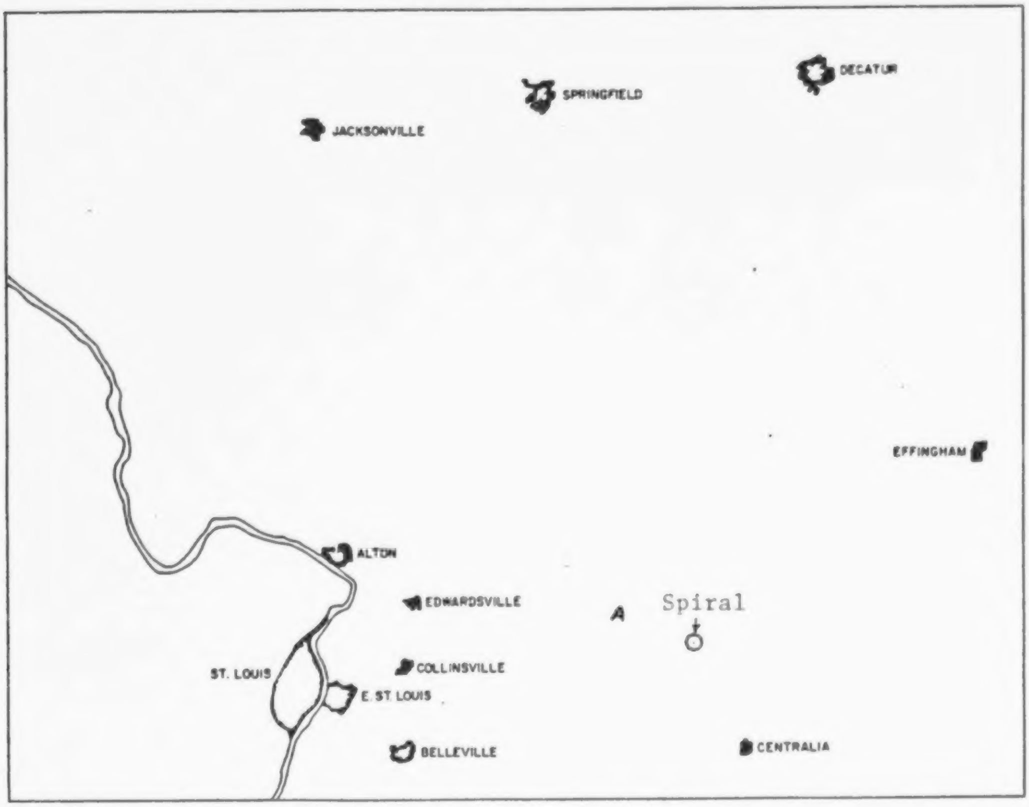
Flight 24
Thursday 8-4-77
Earling Morning 5:22 ⟶ 6:52



Bags

No. 1. 12,000 ft.
No. 2. 5,500 ft.
No. 3. 3,000 ft.
No. 4. 600 ft.
No. 5. PT. A - 1,600 ft.

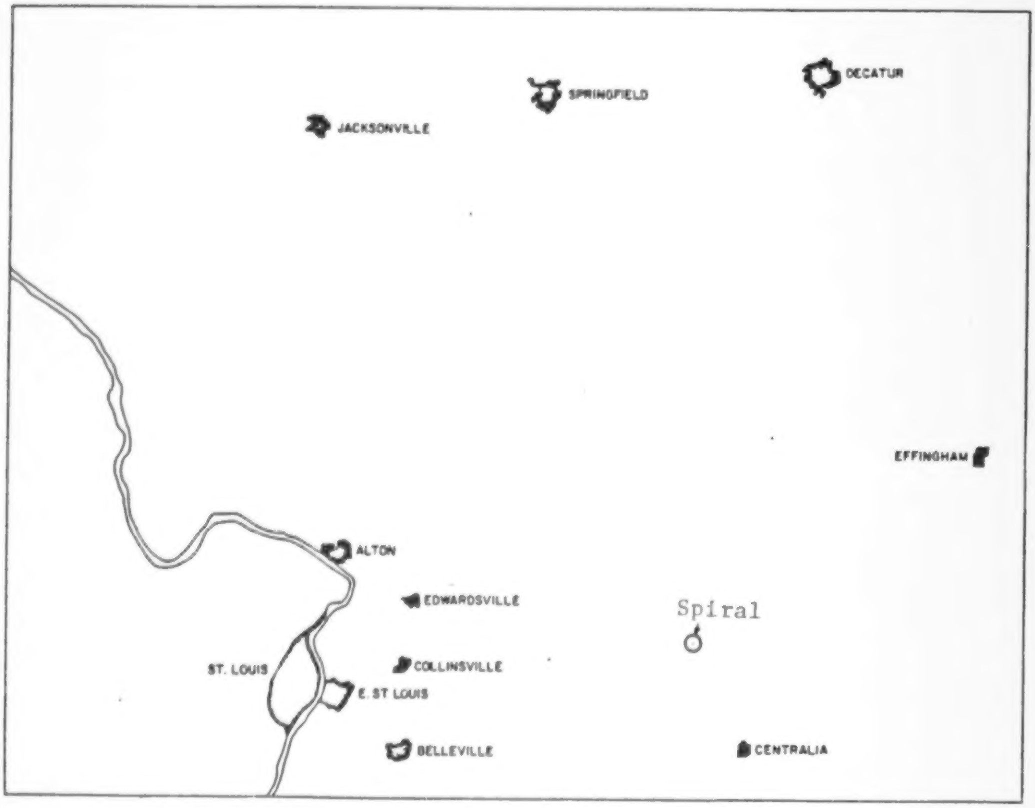
Flight 25
Thursday 8-4-77
Morning 8:08 → 9:36



Bags

No. 1. 12,000 ft.
No. 2. 5,000 ft.
No. 3. PT. A - 1,600 ft.

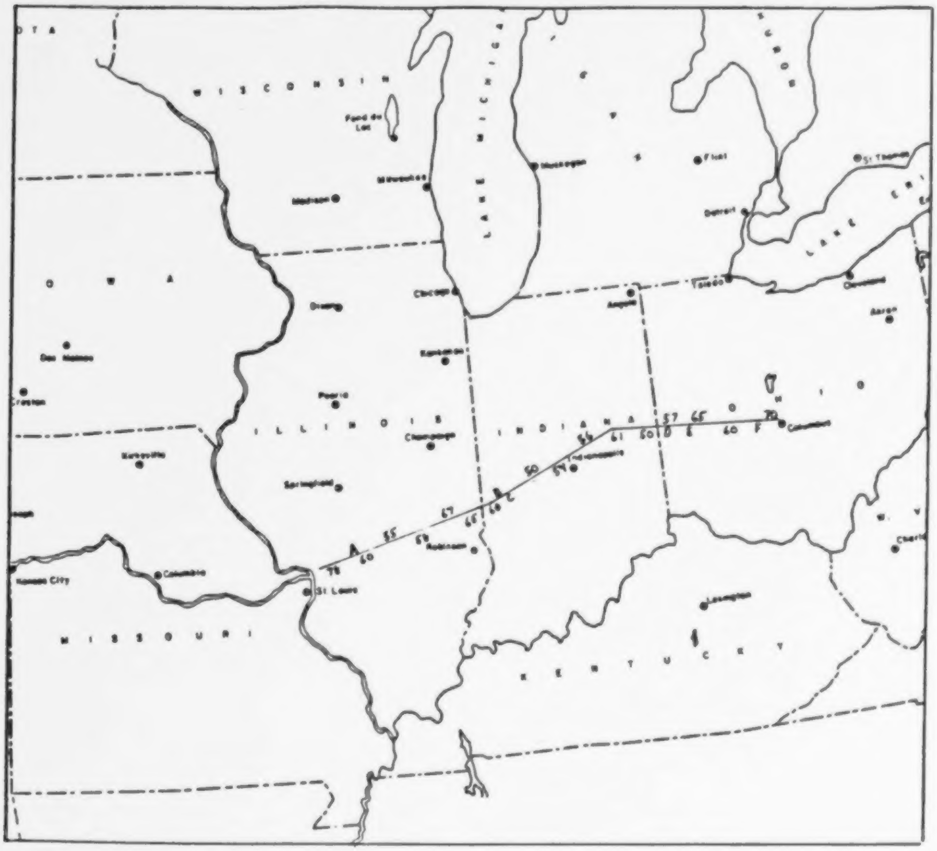
Flight 26
Thursday 8-4-77
Late Morning 10:43 → 12:07



Bags

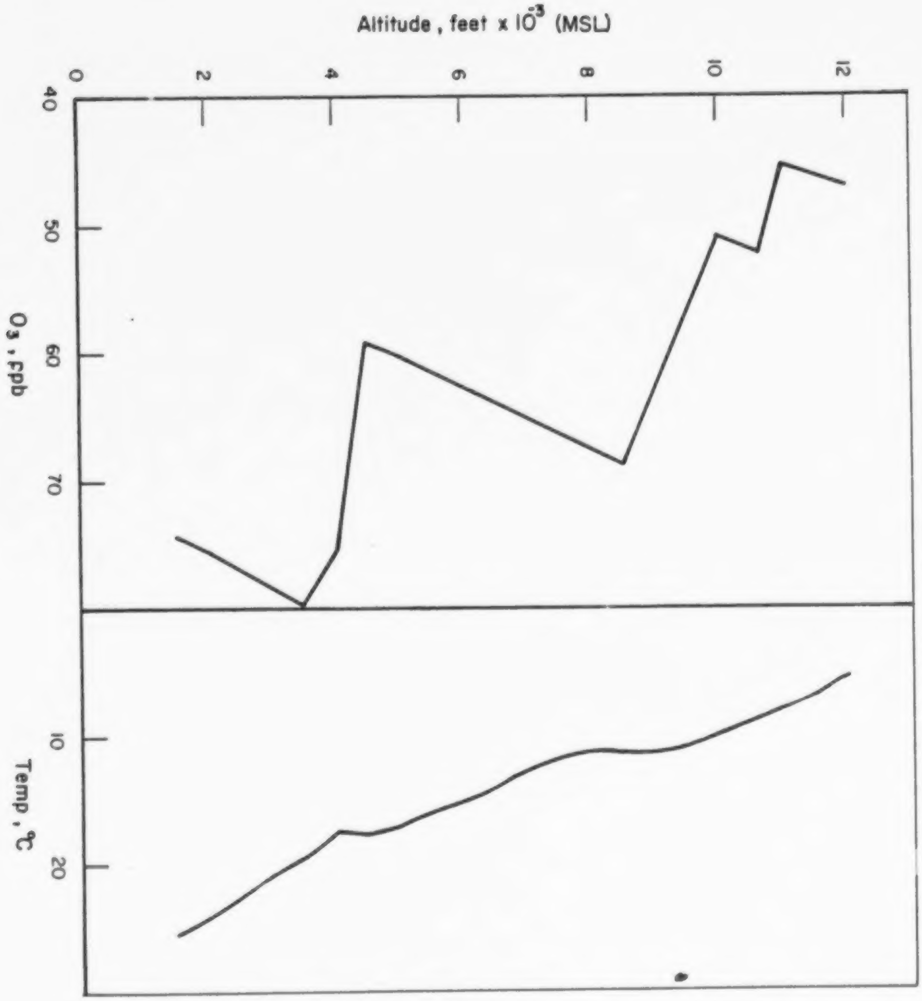
No. 1. 12,000 ft.
No. 2. 5,000 → 4,000 ft.
No. 3. 1,599 ft.

O_3, ppb
Flight 27
Friday 8-5-77
10:45 → 13:00

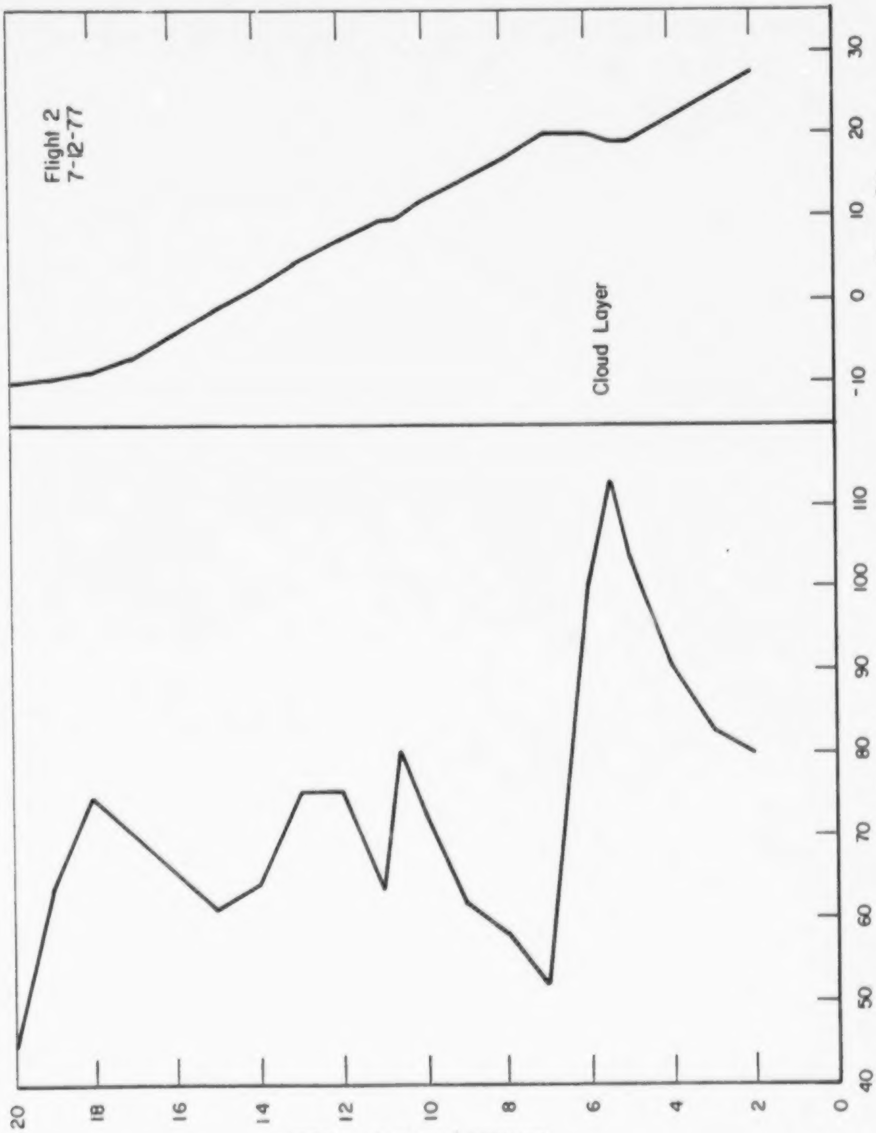


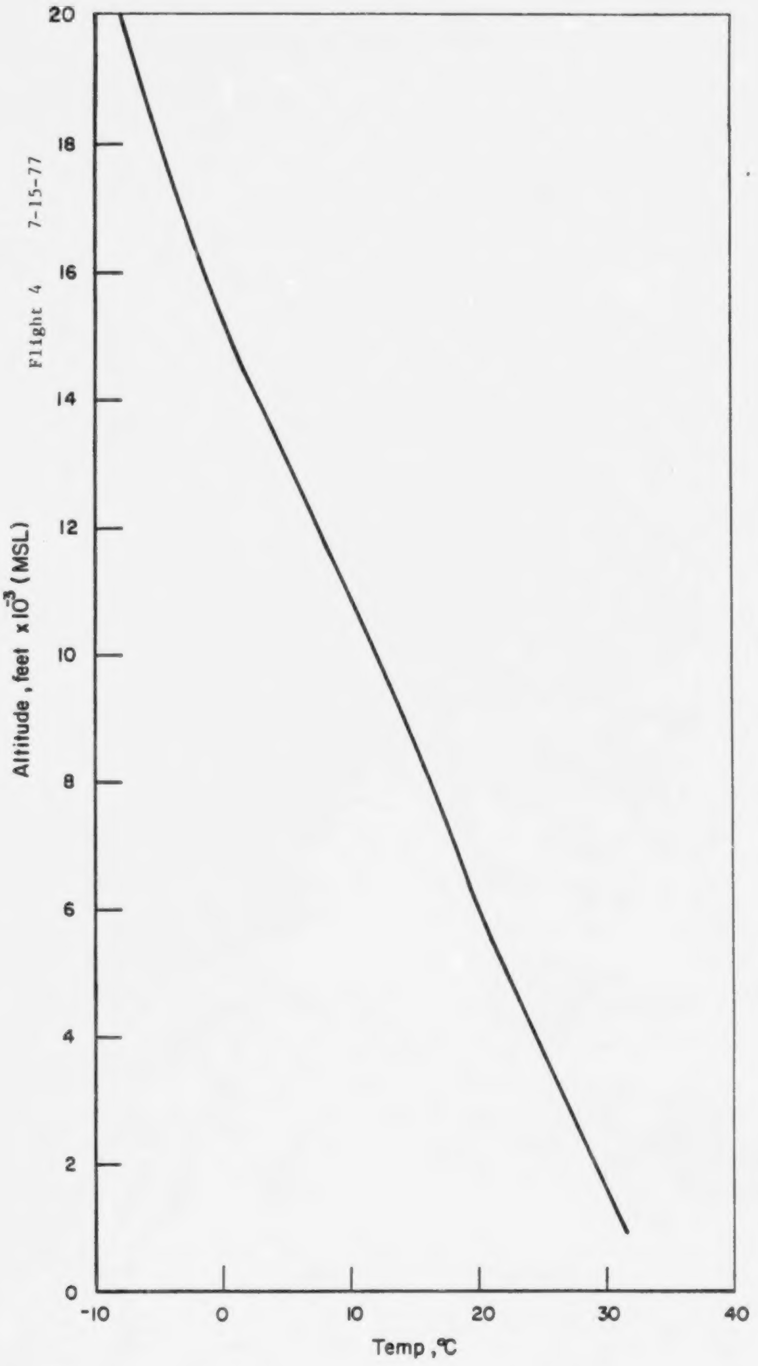
Filters

No. 1. A → B
No. 2. C → D
No. 3. E → F

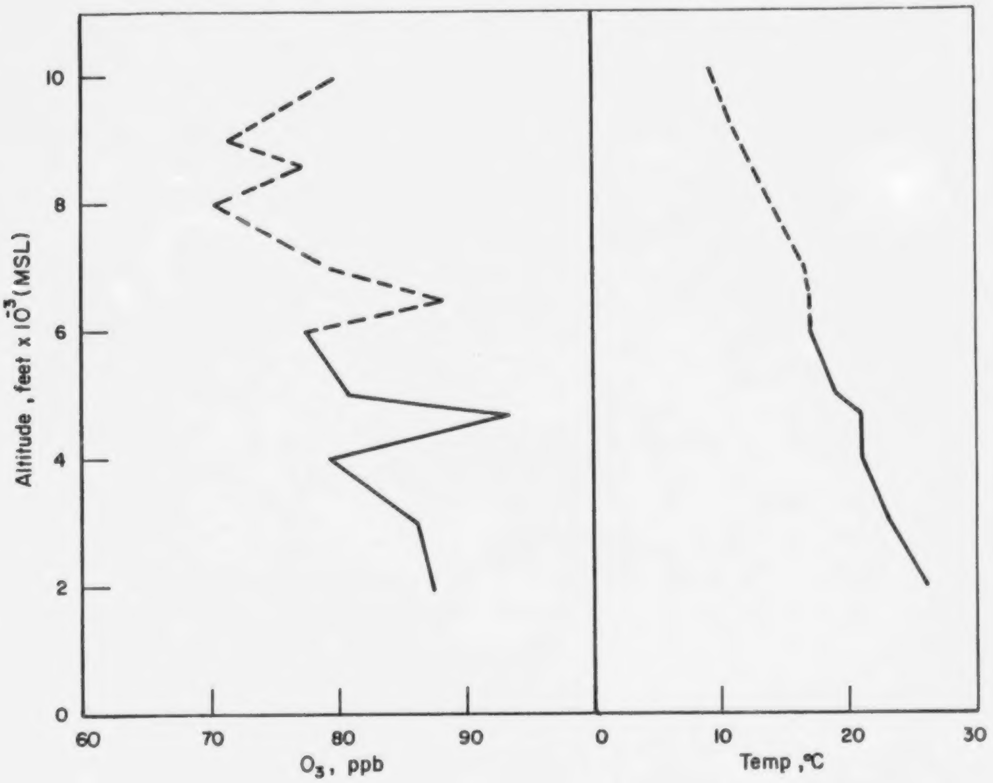


Flight 1 7-9-77

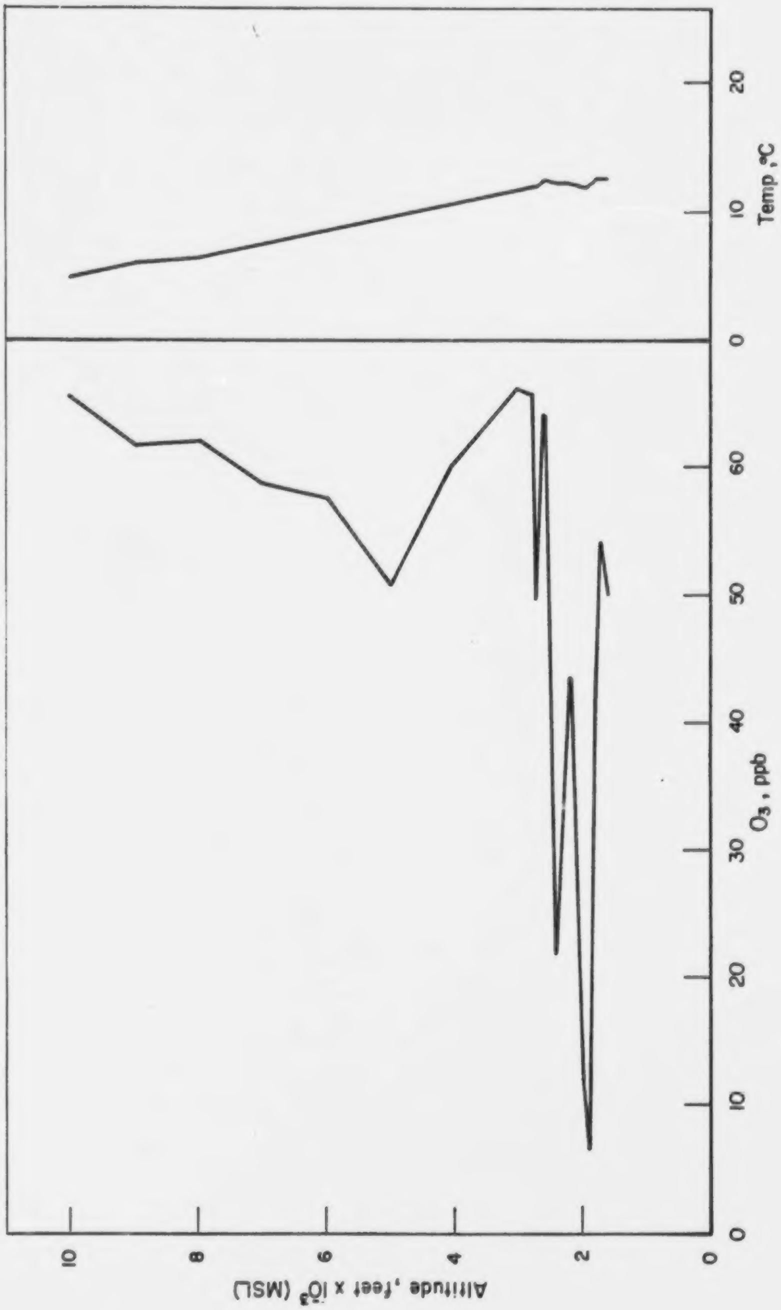

Flight 2
7-12-77
Cloud Layer
Temp., °C
-10
0
10
20
30
O_3, ppb
40
50
60
70
80
90
100
110
Altitude, feet x 10^3 (MSL)
0
2
4
6
8
10
12
14
16
18
20


Flight 4 7-15-77
Altitude, feet x10³ (MSL)
20
18
16
14
12
10
8
6
4
2
0
-10
0
10
20
30
40
Temp, °C

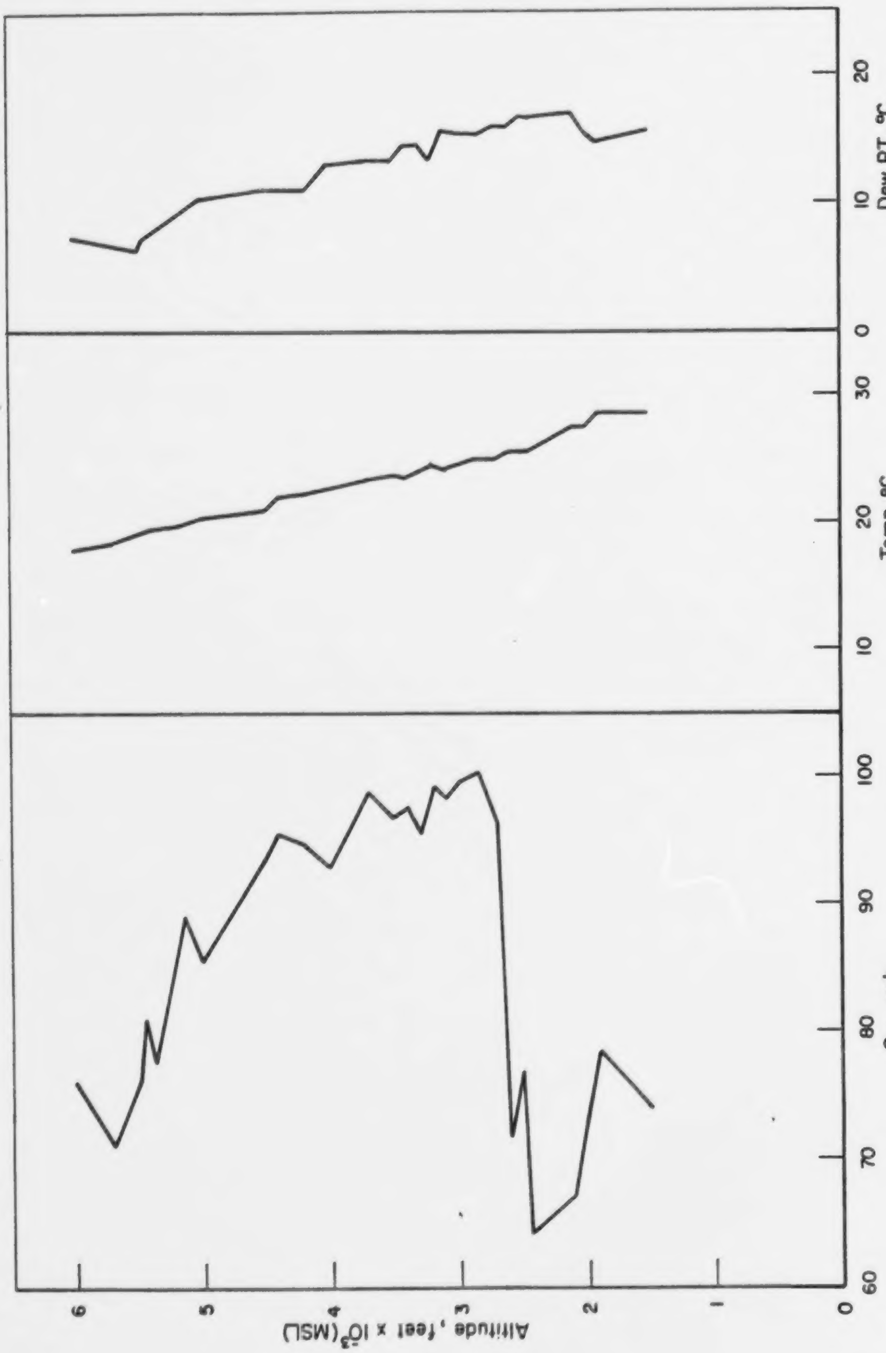
Flight 5 7-20-77



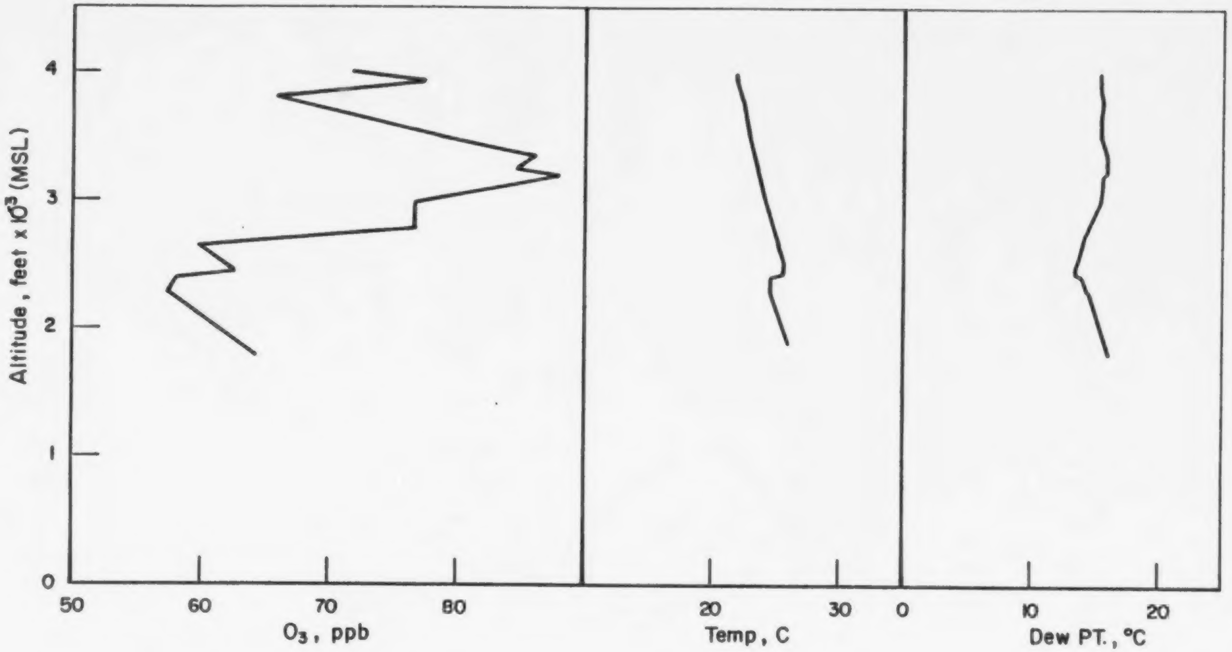
Flight 6 7-21-77

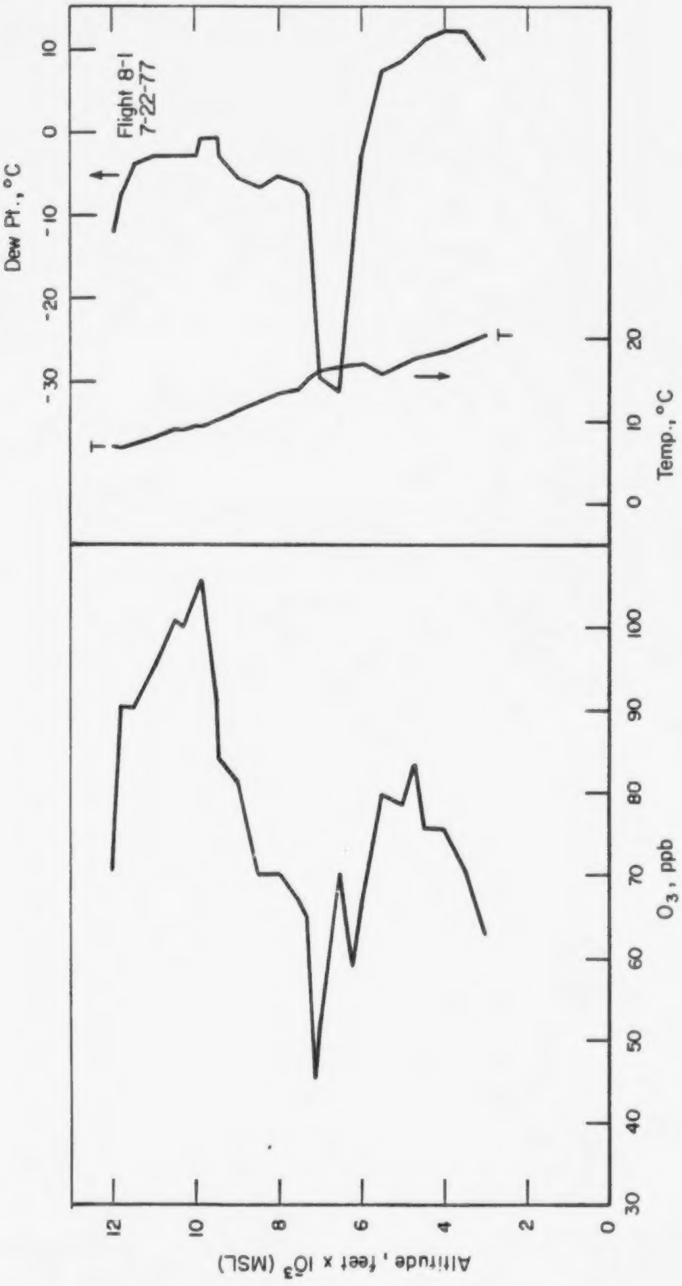


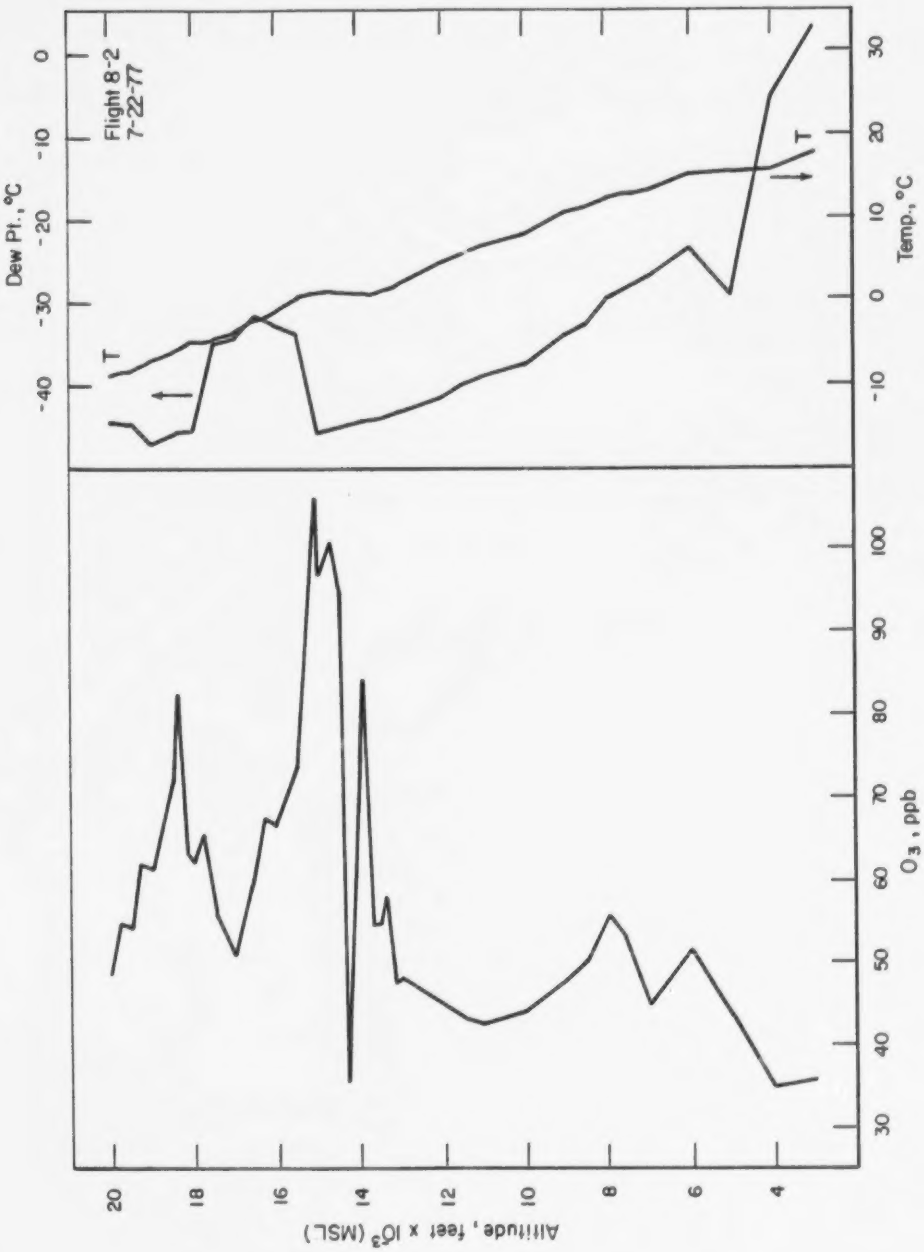
Flight 7-1 7-21-77

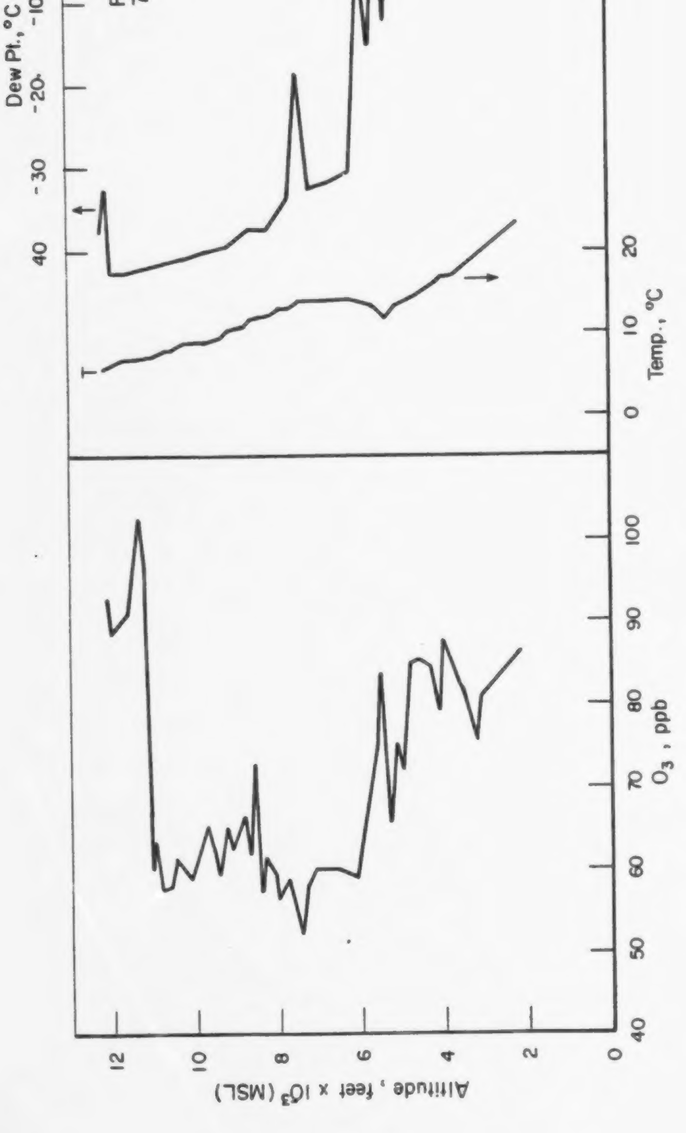


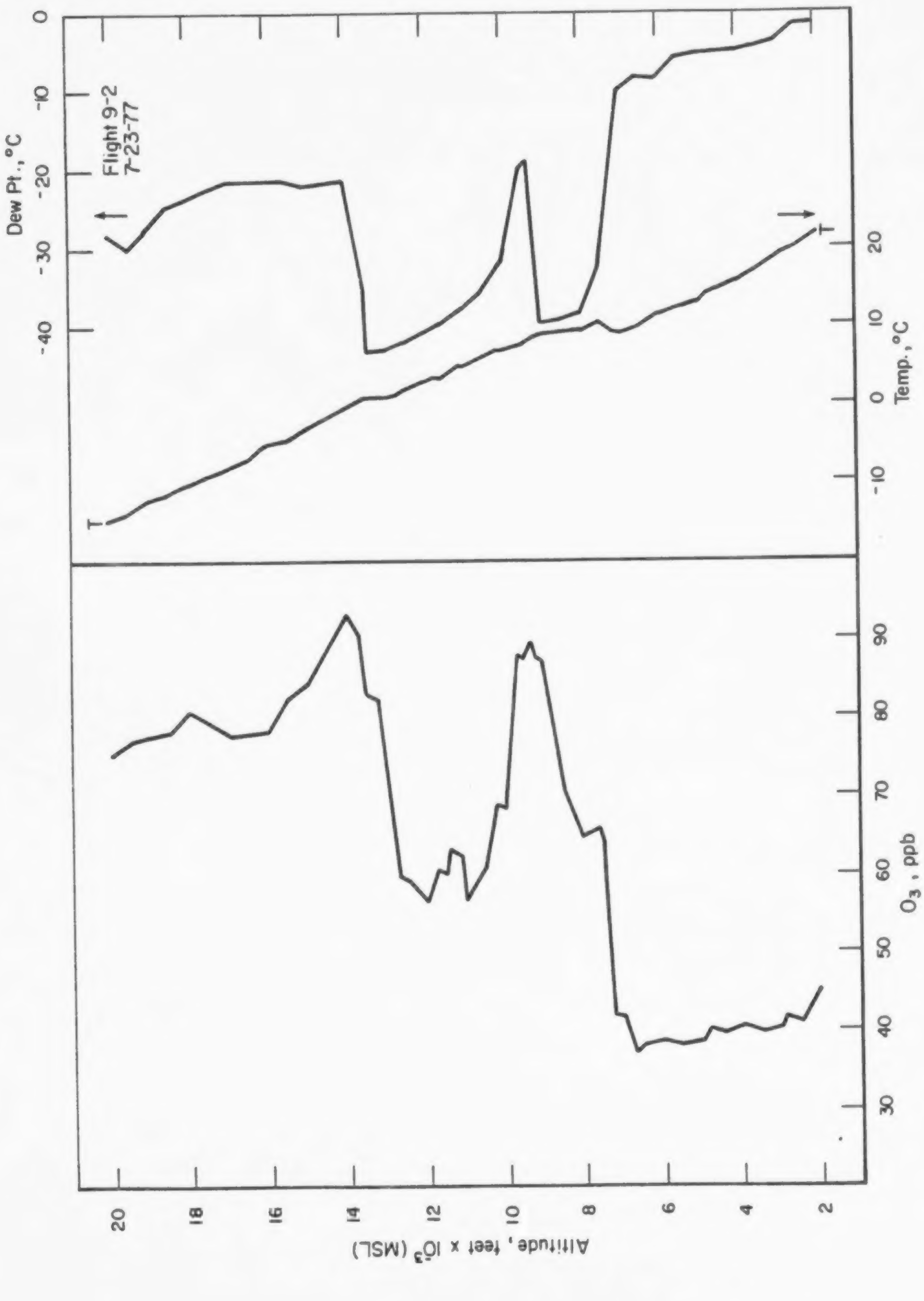
Flight 7-2 7-21-77

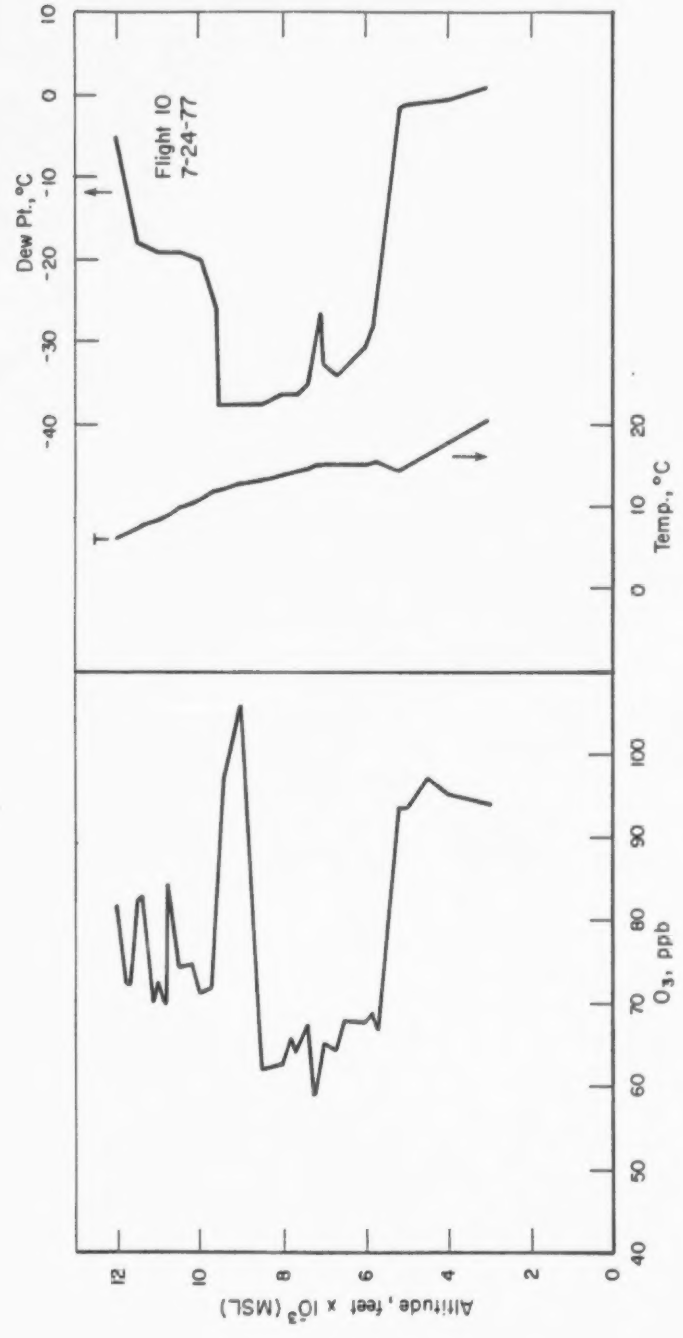



Dew Pt., °C
-30
-20
-10
0
10
Flight 8-1
7-22-77
T
T
Temp., °C
0
10
20
O_3, ppb
30
40
50
60
70
80
90
100
Altitude, feet x 10^3 (MSL)
0
2
4
6
8
10
12

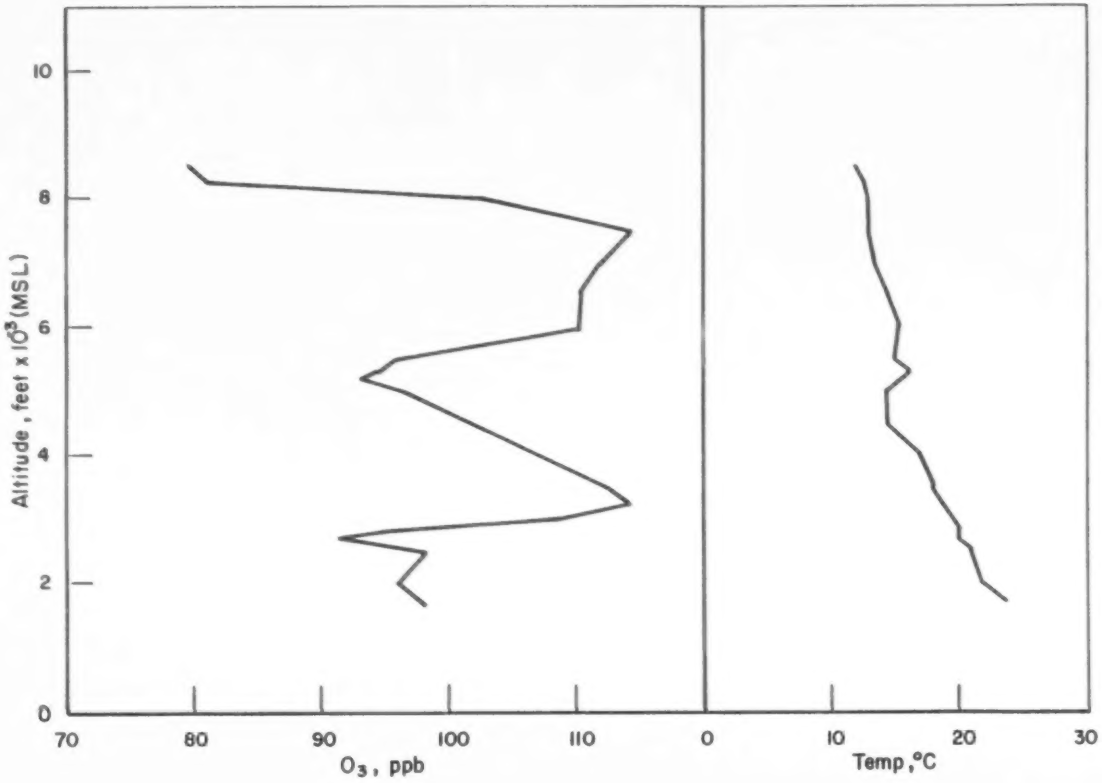

Dew Pt., °C
0
-10
-20
-30
-40
Flight 8-2
7-22-77
T
T
Temp., °C
30
20
10
0
-10
O$_3$, ppb
100
90
80
70
60
50
40
30
Altitude, feet x 10^3 (MSL)
20
18
16
14
12
10
8
6
4

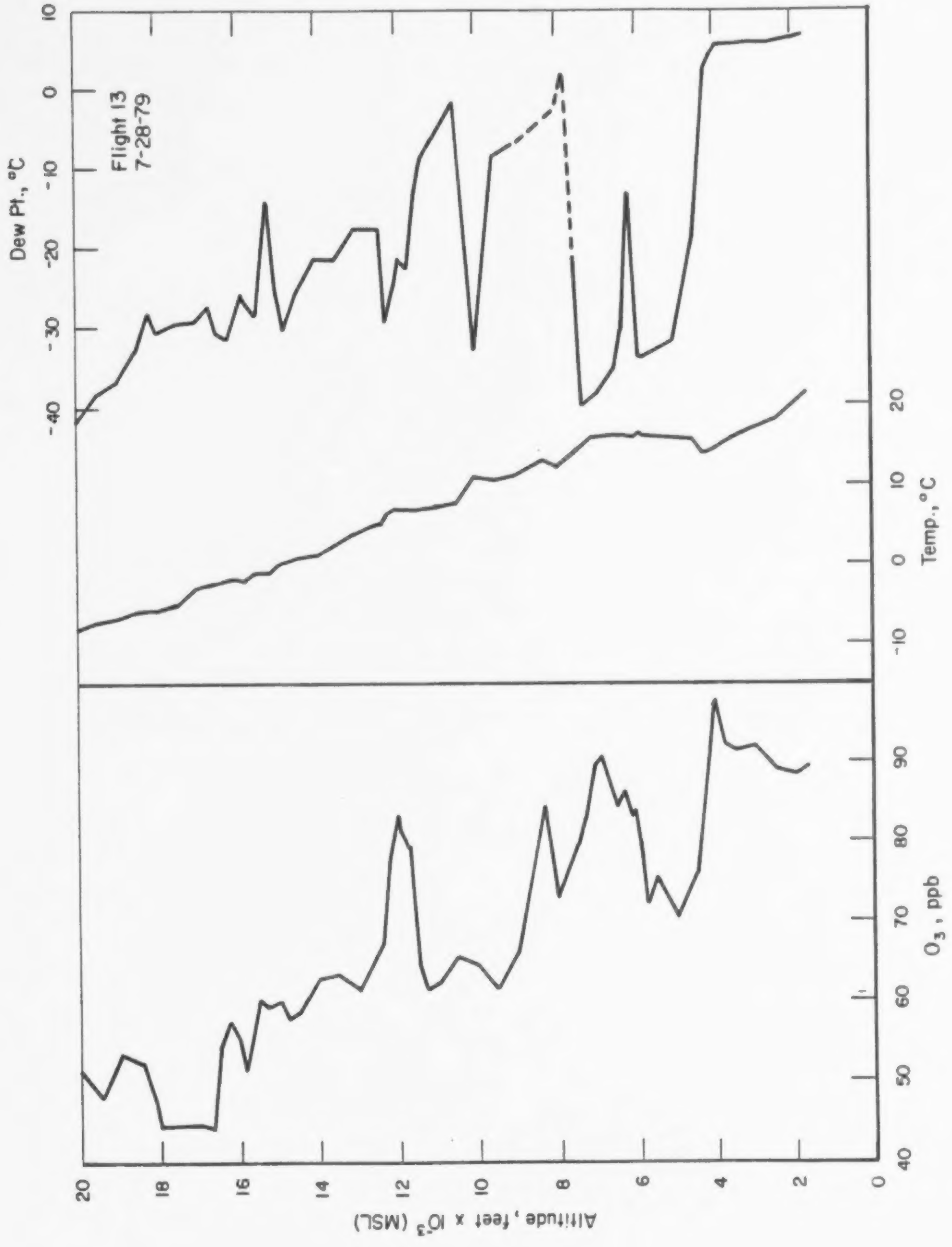

Dew Pt., °C
10
0
-10
-20
-30
40
Flight 9-1
7-23-77
T
Temp., °C
0
10
20
O_3, ppb
40
50
60
70
80
90
100
Altitude, feet x 10^3 (MSL)
0
2
4
6
8
10
12


Dew Pt., °C
-40
-30
-20
-10
0
Flight 9-2
7-23-77
T
T
Temp., °C
-10
0
10
20
O$_3$, ppb
30
40
50
60
70
80
90
Altitude, feet x 10^3 (MSL)
20
18
16
14
12
10
8
6
4
2

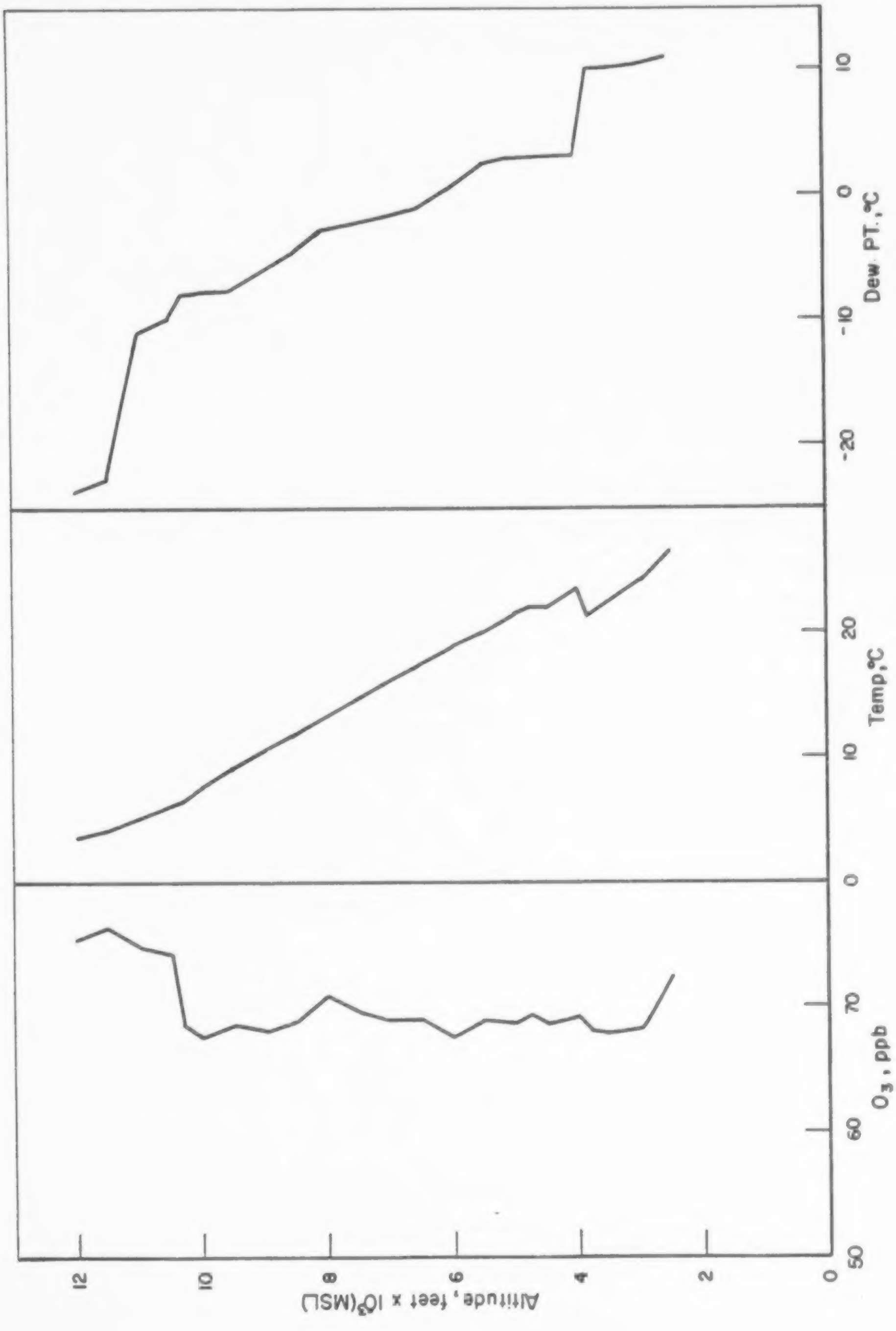

Dew Pt., °C
-40
-30
-20
-10
0
10
Flight 10
7-24-77
T
Temp., °C
0
10
20
O_3, ppb
40
50
60
70
80
90
100
Altitude, feet x 10^3 (MSL)
0
2
4
6
8
10
12

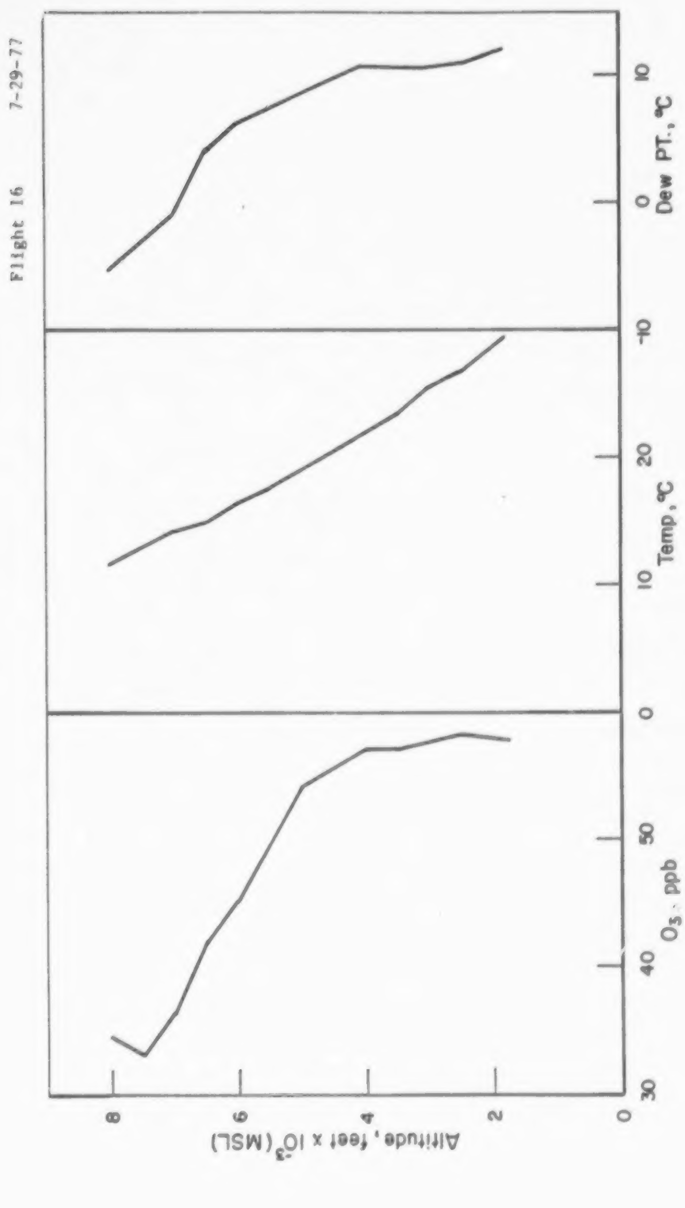
Flight 12 7-27-77




Dew Pt., °C
-40
-30
-20
-10
0
10
Flight 13
7-28-79
Temp., °C
-10
0
10
20
O_3, ppb
40
50
60
70
80
90
Altitude, feet x 10^3 (MSL)
0
2
4
6
8
10
12
14
16
18
20

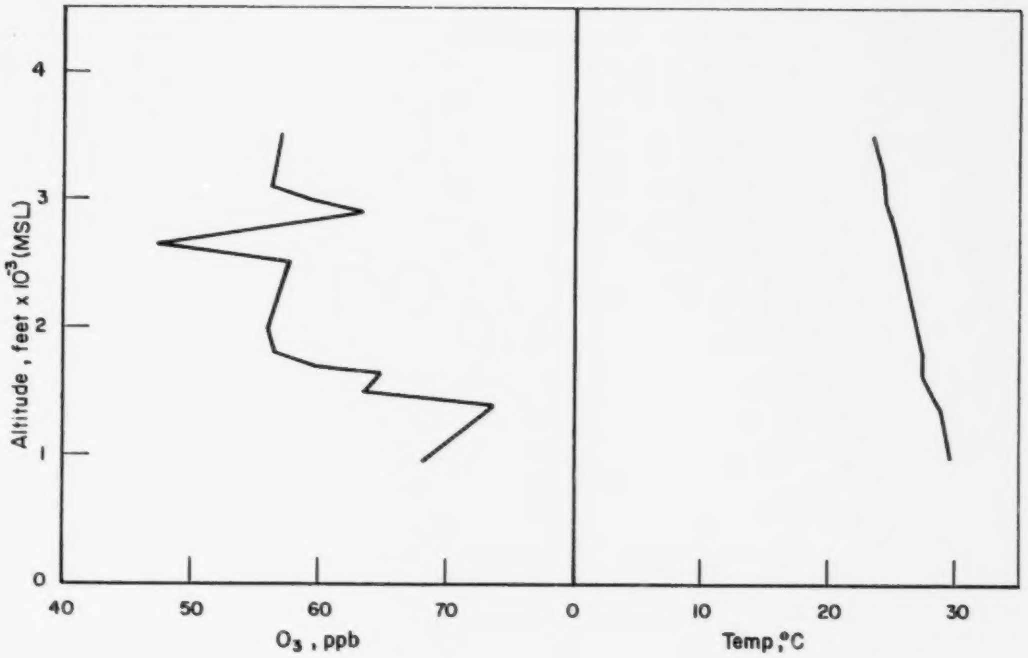
Flight 15 7-29-77

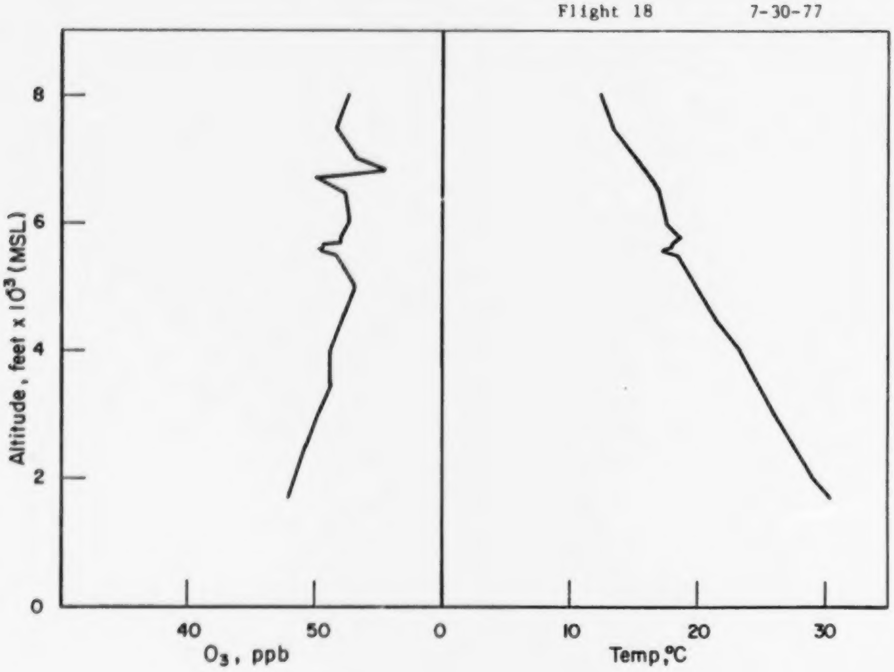




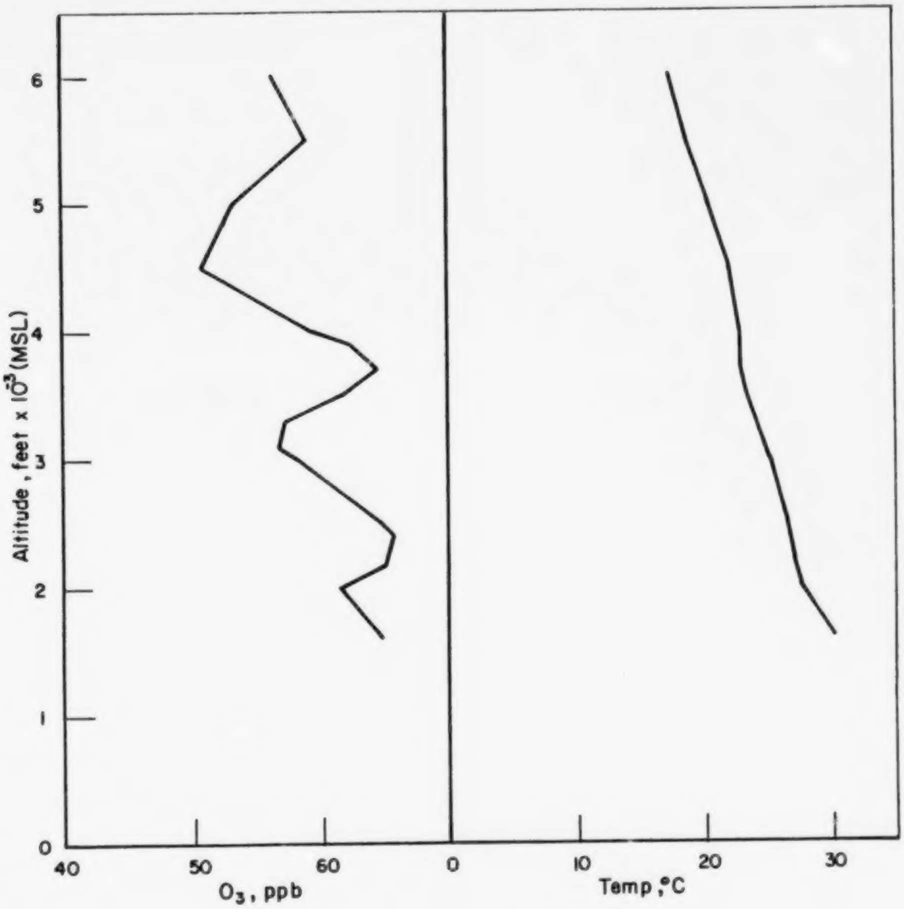
Flight 16 7-29-77

Flight 17 7-30-77

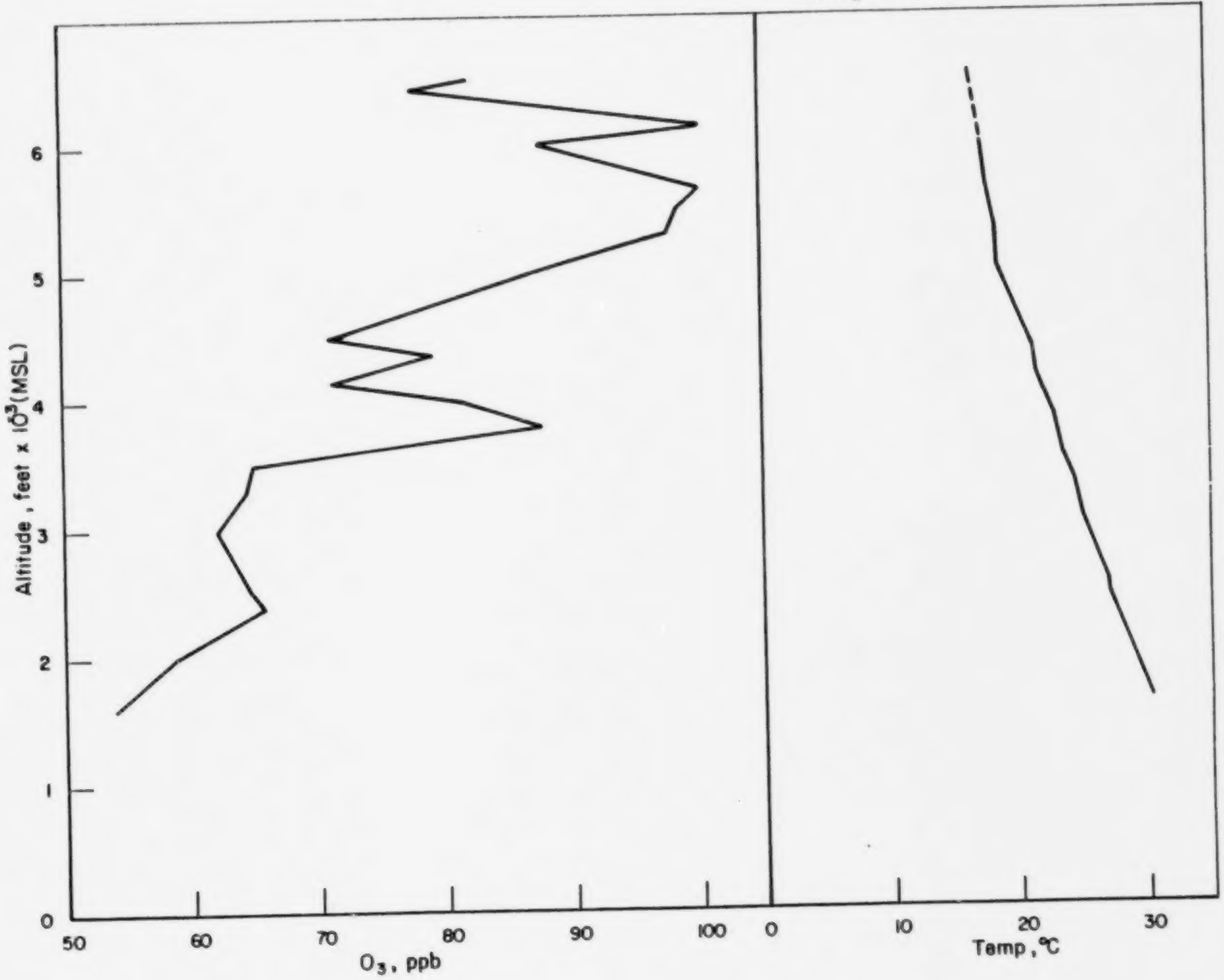


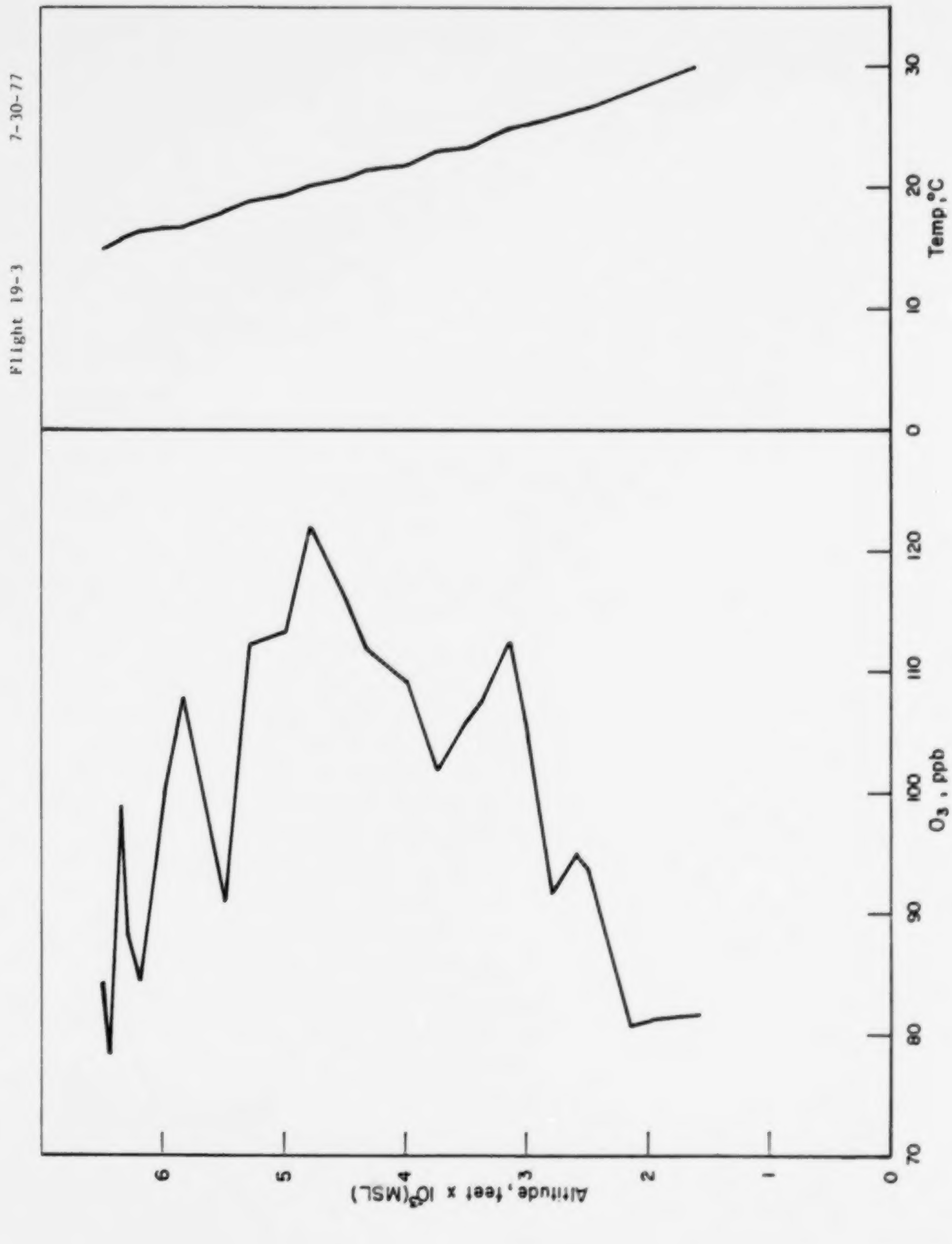

Flight 18
7-30-77
Altitude, feet x 10^3 (MSL)
8
6
4
2
0
40
50
0
10
20
30
O$_3$, ppb
Temp,°C

Flight 19-1 7-30-77

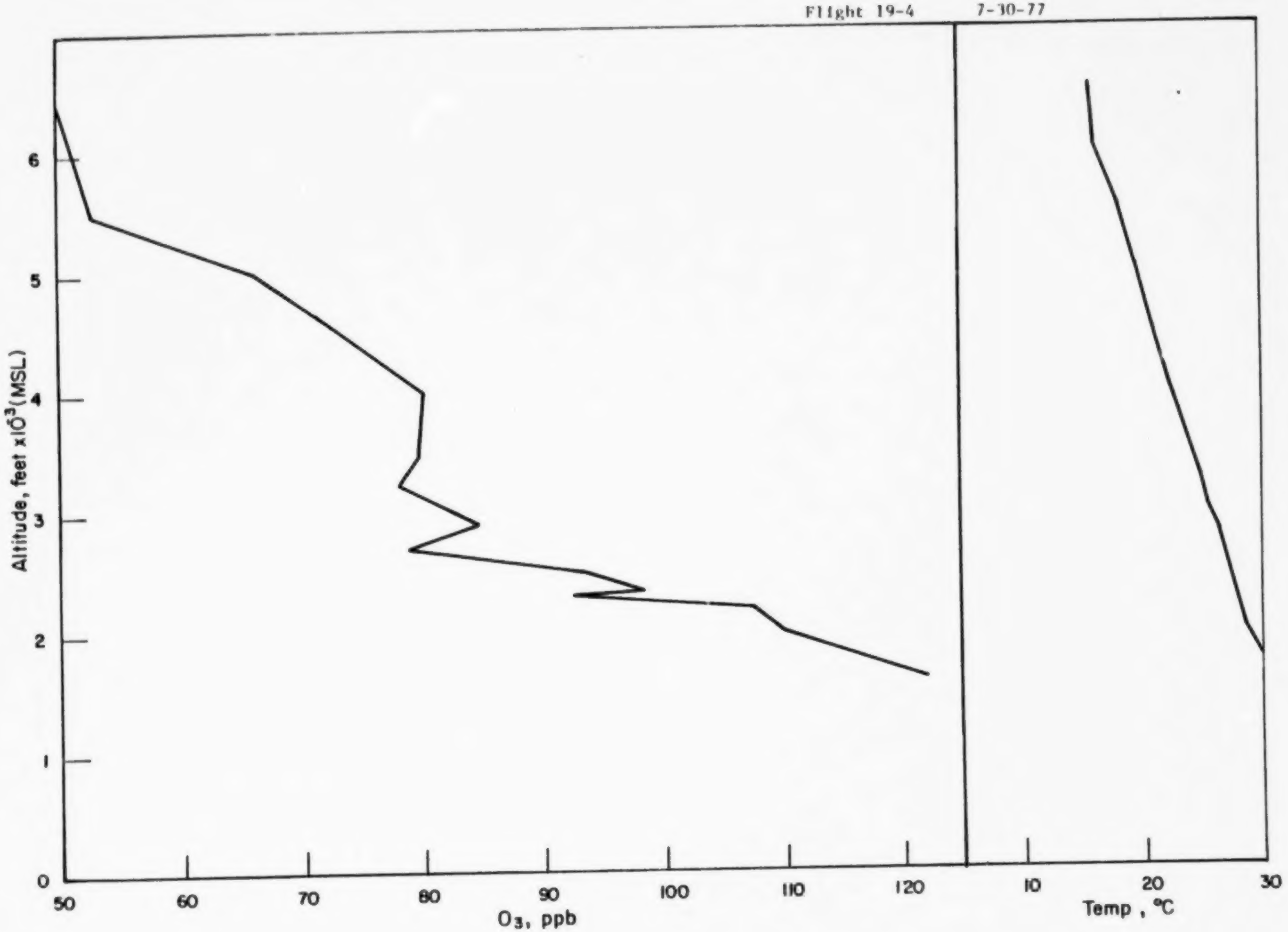


Flight 19-2 7-30-77

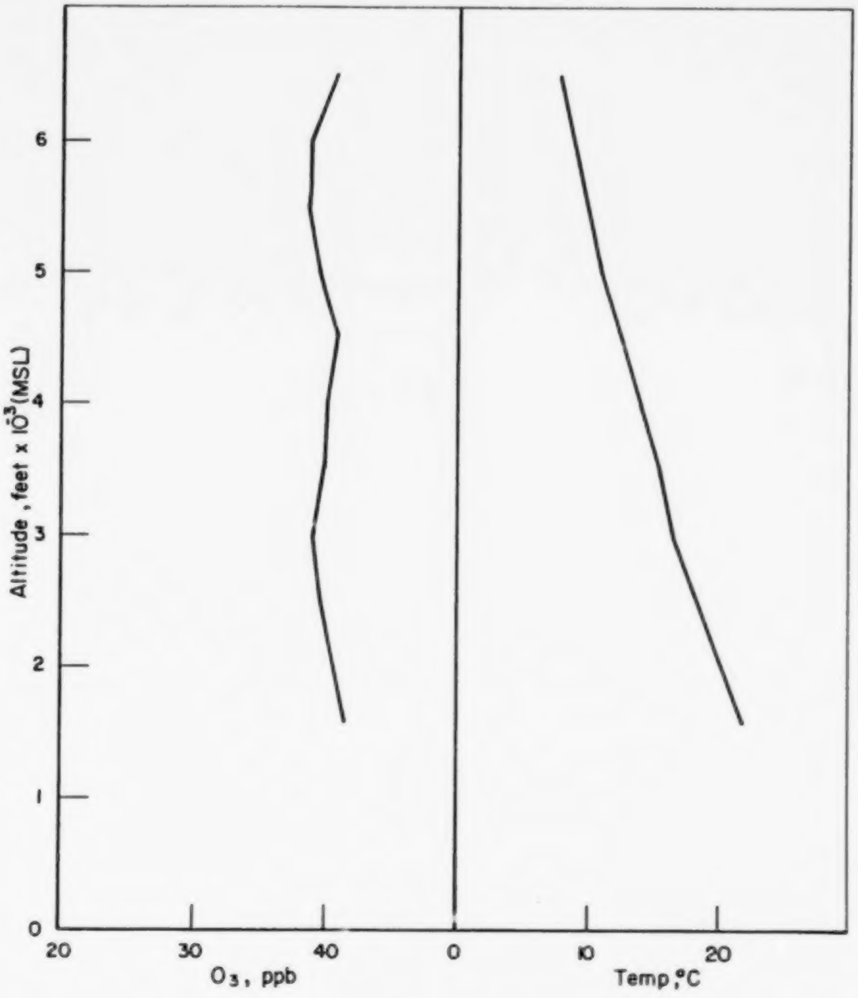


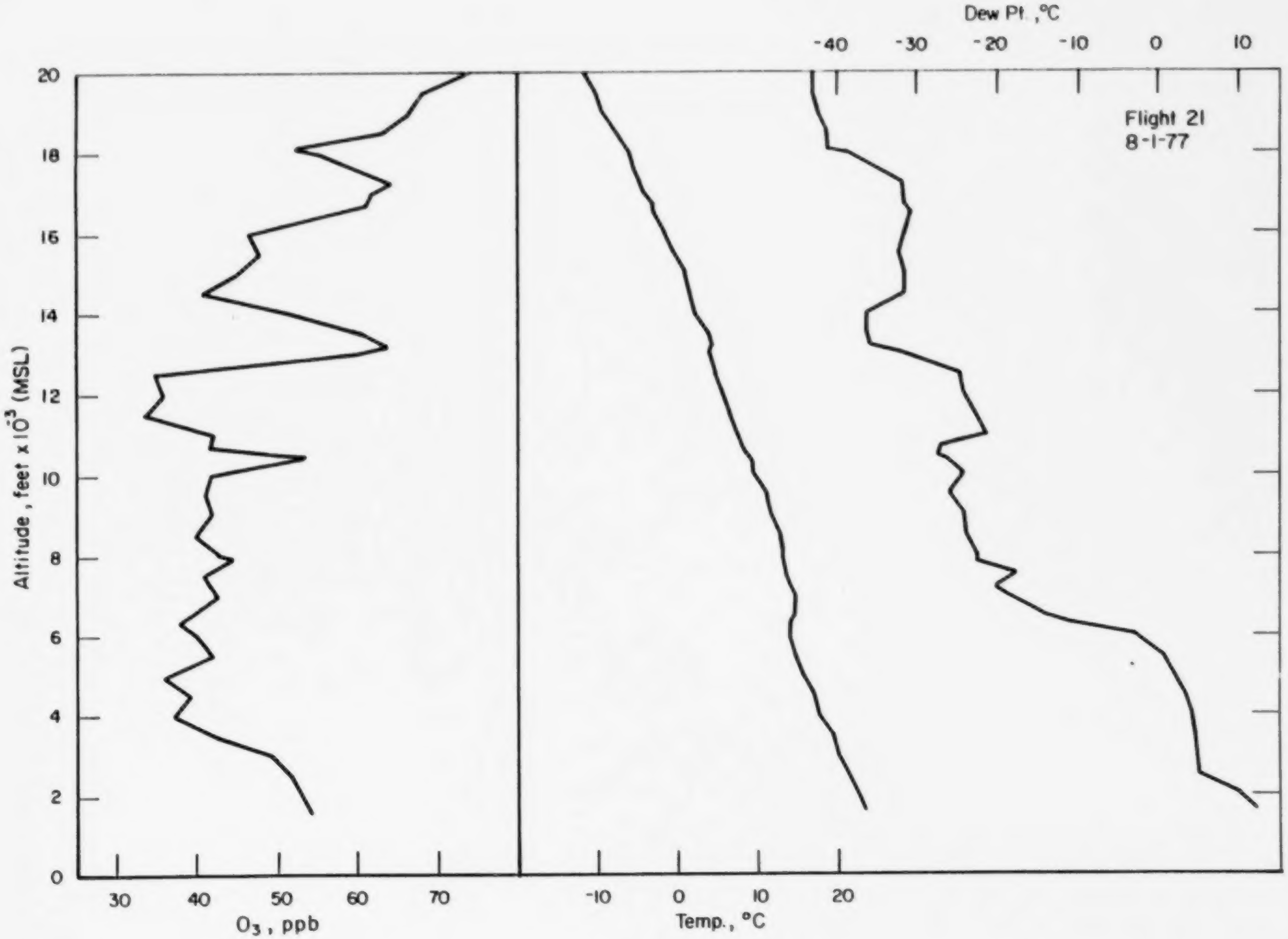

Flight 19-3
7-30-77
Temp,°C
0
10
20
30
O3, ppb
70
80
90
100
110
120
Altitude, feet x 10³(MSL)
0
1
2
3
4
5
6

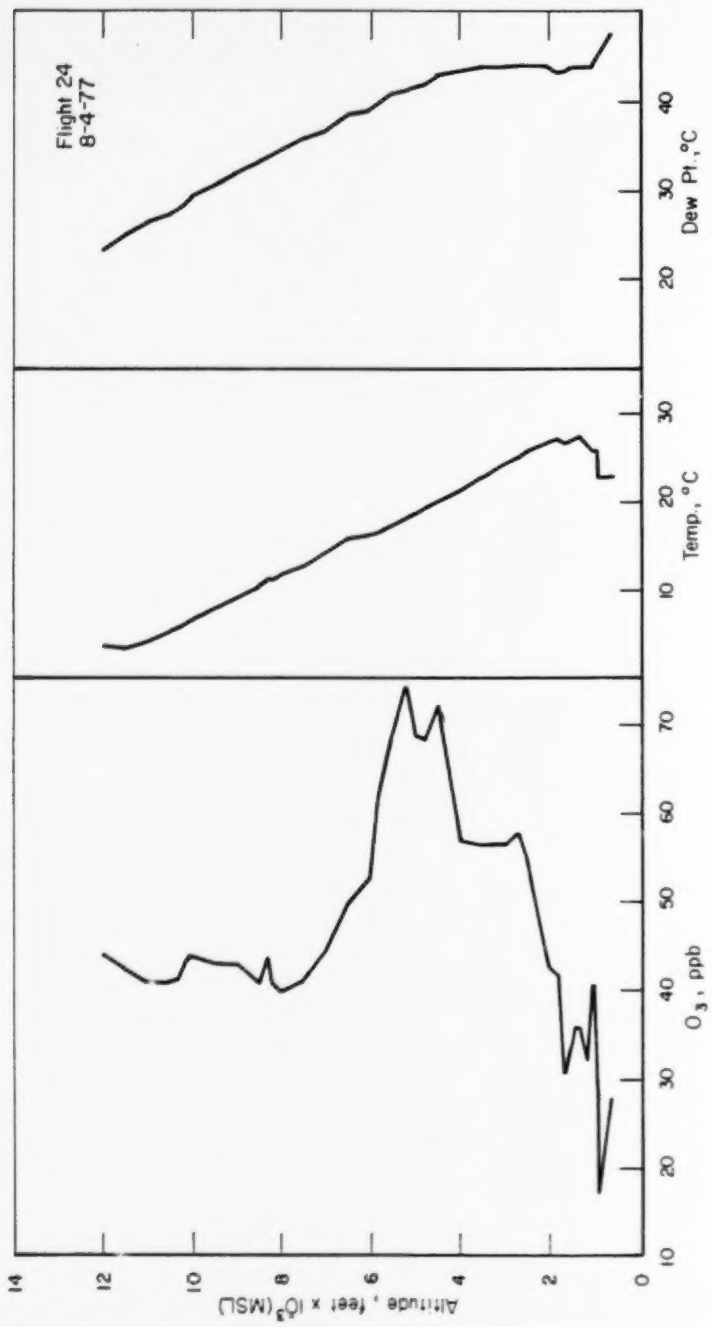
Flight 19-4 7-30-77

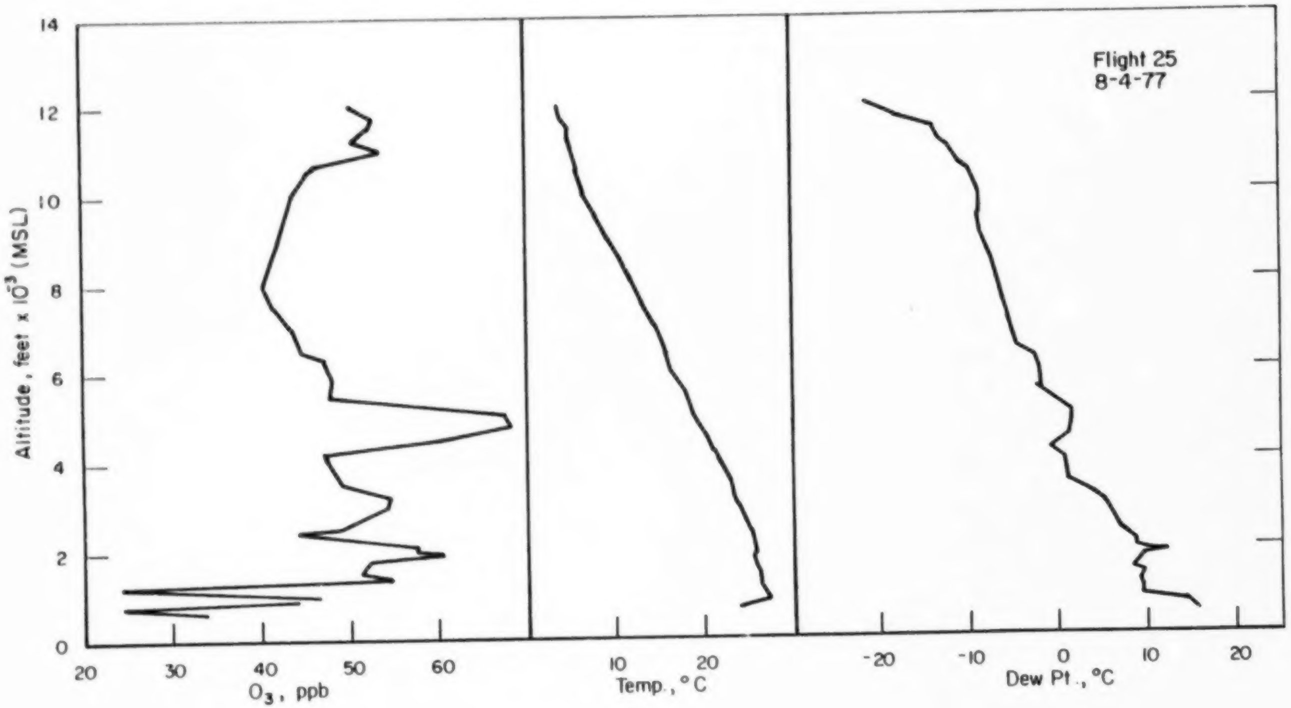


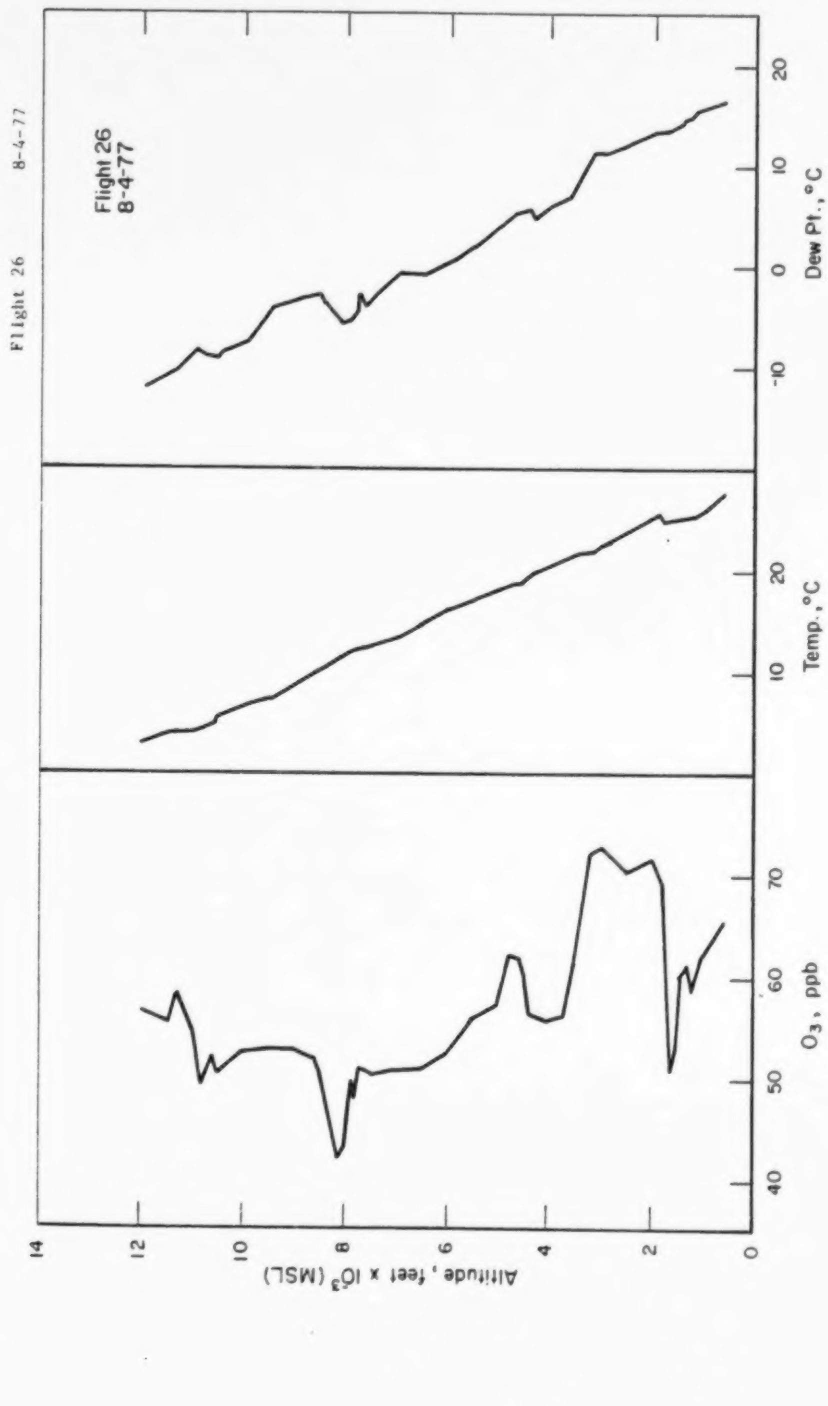
Flight 20   8-1-77




Dew Pt., °C
-40
-30
-20
-10
0
10
Flight 21
8-1-77
Altitude, feet x 10³ (MSL)
20
18
16
14
12
10
8
6
4
2
0
30
40
50
60
70
O₃, ppb
-10
0
10
20
Temp., °C


Flight 24
8-4-77
Dew Pt., °C
20
30
40
Temp., °C
10
20
30
O$_3$, ppb
10
20
30
40
50
60
70
Altitude, feet x 10^3 (MSL)
0
2
4
6
8
10
12
14


Flight 25
8-4-77
Altitude, feet x 10^3 (MSL)
0
2
4
6
8
10
12
14
20
30
40
50
60
O_3, ppb
10
20
Temp., °C
-20
-10
0
10
20
Dew Pt., °C


Flight 26
8-4-77
Flight 26
8-4-77
Altitude, feet x 10³ (MSL)
14
12
10
8
6
4
2
0
40
50
60
70
O₃, ppb
10
20
Temp., °C
-10
0
10
20
Dew Pt., °C